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Parametric study andoptimization of water-tanks

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Enginyeria de la Construcció

Barcelona, Setembre de 2014.

Departament d'Enginyeria de la Construcció

TREBALL FINAL DE GRAU

"If we become aware of its limitations and compulsions, we can transcend them"

- BKS Iyengar

ACKNOWLEDGMENTS

En primer lugar, agradecer a mis tutores Albert de la Fuente y Pablo Pujadas por darme la oportunidad de realizar este trabajo. Por su plena dedicación, constante orientación y por sus valiosos consejos, que han contribuido a mi crecimiento durante las diferentes fases de este trabajo.

Agradecer también a Alejandro Josa por su disposición para ayudarme y por sus más que útiles contribuciones. A David San Juan por su acertada colaboración, su paciencia, comprensión y disposición durante los meses de campaña para la obtención de datos y resultados, y a la vez durante toda la elaboración del presente trabajo. Y al grupo de trabajo compuesto por Nuria y Anna, ha sido un placer trabajar en paralelo con vosotras.

A todos los amigos, compañeros y grandes personas que he conocido a lo largo de estos años compartidos en la carrera. En especial a Marta, Héctor y Marina, con quienes he compartido los mejores momentos. El gran grupo de personas que me llevo en esta etapa ha contribuido a que hoy sea mejor y más fuerte que cuando la empecé.

Para finalizar, esta breve relación de agradecimientos a mis padres, Ricardo y Belén, y a mis hermanos, Sofía, Ricardo y Borja. Gracias al apoyo de todos he llegado hasta aquí. Y sobretodo, gracias a mis padres por enseñarme el valor del esfuerzo, la constancia y humildad como camino del éxito, tanto personal como profesional.

A todos, GRACIAS

.

ABSTRACT

The study aims to improve the optimization of the resources required to the design and construction of water tanks. The criteria and methodology proposed by the standards and studies is analyzed and have contributed to develop the structural design and the associated parametric study. Likewise, the methodology applied to develop the environmental analysis; Life Cycle Assessment (LCA) is addressed.

The present work consists of two studies that has been developed at the same time and which complement each other. The structural and the environmental study conducted by an interdisciplinary group from two universities: Universitat Autònoma de Catalunya (UAB), in terms of the environmental study; and Universitat Politècnica de Catalunya (UPC) for implementing the structural analysis.

Regarding to the structural part, the study carried out consists in analyzing the rectangular and cylindrical reinforced concrete tanks in order to optimize the materials required to meet with the criteria established for its structural design. The parametric study was carried out thanks to a program developed in the present work and designed in accordance with the actual codes. The program calculates the amounts of materials required for the design and construction of reinforced concrete reservoirs, especially the amount of armor to deal with the efforts and the amount of concrete. One program for each tank typology has been developed, one for the rectangular configuration and another for the cylindrical typology.

In the environmental analysis, the several indicators and the impacts generated by each case structurally analyzed, in terms of materials consumption, have been studied. The LCA plays an important role to provide the criteria in order to choose the optimal configuration between the different solutions.

Finally, general and particular conclusions from the studies developed are presented.

RESUMEN

El estudio que se presenta tiene como objetivo mejorar la optimización de los recursos necesarios para el diseño y posterior construcción de depósitos de agua. Se ha analizado y utilizado la metodología propuesta en la normativa y estudios para el desarrollo de la casuística a analizar. A su vez, también de analiza y presenta la metodología aplicada en el desarrollo del análisis ambiental, el Análisis del Ciclo de Vida (ACV).

El presente trabajo consta de dos estudios que se han realizado de forma conjunta y complementaria. El estudio estructural y el estudio ambiental realizado a través de un grupo interdisciplinar entre dos universidades: Universitat Autònoma de Catalunya (UAB), para el desarrollo del estudio ambiental; y la Universitat Politècnica de Catalunya (UPC) para la realización del análisis estructural.

En cuanto al estudio estructural, se ha realizado un análisis de los depósitos rectangulares y circulares de hormigón armado, con el fin de optimizar los materiales necesarios para cumplir con los criterios establecidos para su diseño estructural. El estudio se ha realizado gracias a un programa desarrollado en el presente trabajo, de acuerdo con las normativas actuales. El programa consiste en calcular las cantidades de materiales necesarias para el diseño y construcción de los depósitos, especialmente la cantidad de armaduras para hacer frente a los esfuerzos y la cantidad de hormigón. Se ha desarrollado uno para cada tipología analizada, depósitos rectangulares y cilíndricos.

En el análisis del medio ambiente, se han definido los diferentes indicadores a estudiar y el impacto generado por cada uno de los casos estructuralmente analizados, en términos de consumo de materiales. El ACV juega un papel muy importante ya que proporciona el criterio de cara a escoger entre las posibles soluciones óptimas.

Finalmente, se presentan las conclusiones generales y particulares de los estudios desarrollados.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Water tanks are very common structures due to the important role they play such as the supply of drinking water to populations. Reinforced concrete tanks are one of the most common structures when it has to do with water and wastewater storage and treatment. They are widely used to store large quantities of water in urban and rural water supply schemes.

Today water tanks have taken on many shapes and configurations. From design point of view the tanks may be classified as per their shape. Among them we will study the rectangular and cylindrical reinforced concrete tanks. Both typologies will be studied through three different configurations according to their position on the field: (1) Partially buried tanks; (2) Surface tanks and (3) Buried tanks.

In the pages that follow, the reader will be introduced to the concept of a water tank and the importance that the structural design plays in the long-term proper performance of the structure. This work consists on performing a detailed parametric study on different structural types and shapes water tanks.

1.2 OBJETIVES

The aim of this work is to conduct an analysis from both: the structural point of view (section analysis, reinforcement, etc.) and the associated optimization of the resources needed for the construction of such elements through and environmental analysis. Taking that into account, three general objectives that correspond to the main subjects addressed in this work are defined as follows.

- Study and analyze the design of water tanks through the calculation and design for different volumes and under different shape typologies described above.

- Analyze the results and make abacuses of the main parameters involved in the design of such type of elements (such as thickness of the deposit, armor and reinforcement, geometrical dimensions) according to the shape typology and volume of the tank to define ranges that optimize the design from the structural point of view.

- In order to obtain the environmental impacts of the structural solution and find the optimal solution, impact-volume curves for each shape-typology must be assessed.

In order to achieve the main goals several specific objectives are set. Table 1.1 shows the main specific goals for each subject treated in the present work.

Table 1.1 Specific objectives

Goal	Specific objective
Structural calculation performance	• To collect different existing criteria regarding the methodologies applied for the analysis and calculation of water tanks. • To perform a calculation program, which provides the main outputs required to develop the parametric study.
Structural parametric study	• To select a large variety of representative cases of rectangular cylindrical water tanks comprising realistic ranges of volumes, dimensions, wall thicknesses and positions. • To determine which the optimal wall thickness is for each volume defining a curve where the materials consumptions are shown. • To determine which configuration requires the less material consumption for a given volume in both typologies, rectangular and cylindrical. • To study in depth the cylindrical cases depending on the variables involved in the parametric study in order to provide conclusions that must agree with the further environmental assessment.
Environmental assessment	• To select a number of representative cases of cylindrical water tanks comprising realistic ranges of volumes dimensions and positions previously structurally assessed. • To analyse the environmental impacts of the structurally optimised designs following the LCA methodology. • To determine which the optimal water tank is for each volume and define a curve for the calculation of the environmental impacts of the optimal cases. • To determine the optimal water tank for each volume analysed in order to define a curve for the costs generated of the optimal cases.

1.3 METHODOLOGY

This work is subdivided into six chapters, some references and appendix as shown in Figure 1.1. The introduction and the main subjects to go through the document in the first and second chapter are explained. At this point, parametric study is realized, which will be used to develop the environmental analysis.

- In Chapter 1, the general specific objectives along with the methodology applied to achieve them are presented.
- Chapter 2 provides the state of the art of the subjects treated in this work.
- In Chapter 3, the calculation performance to provide the structural results is explained with all the steps followed.
- In Chapter 4, the parametric study is presented and the results are discussed.
- Chapter 5 presents the environmental analysis, and the impacts provided are discussed.
- Conclusions and outlooks of this work are provided in Chapter 6.

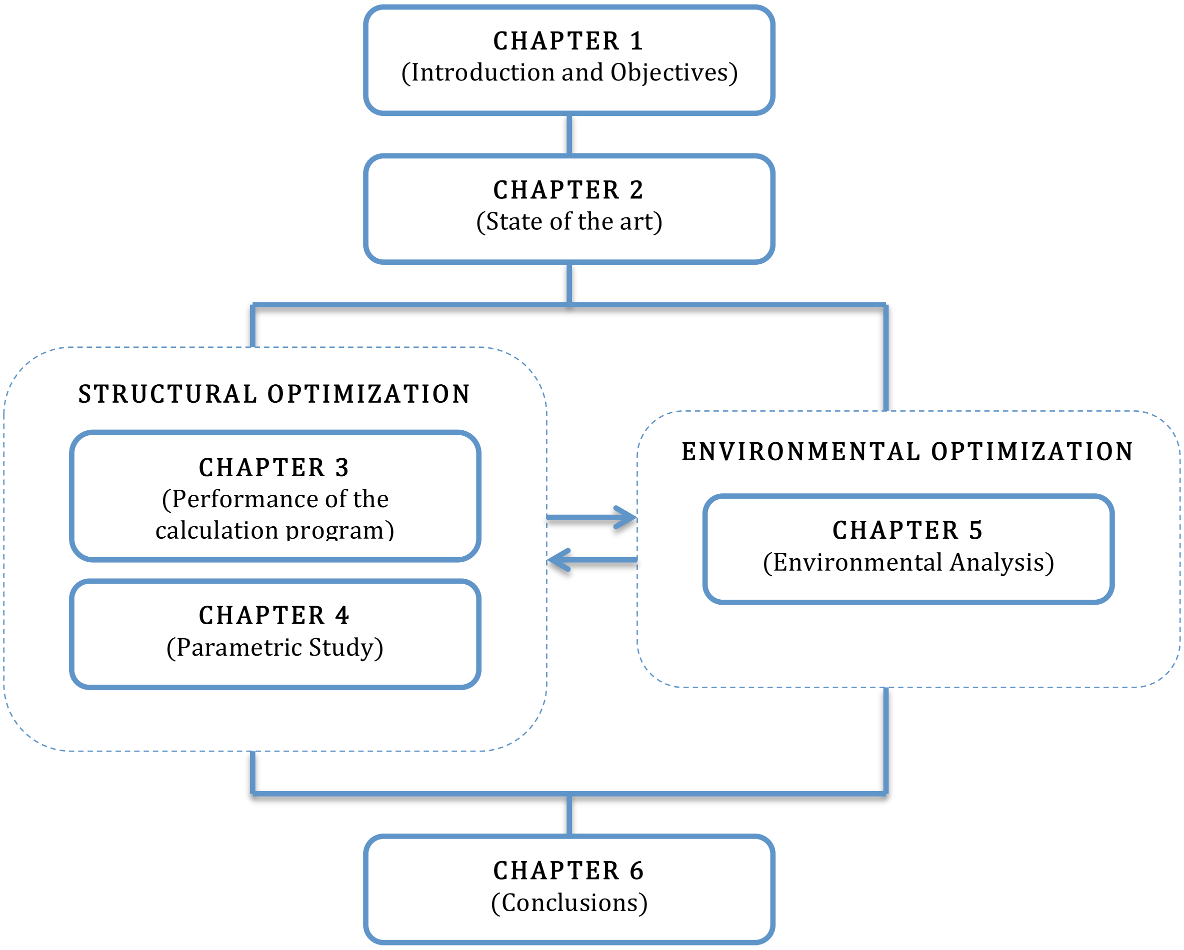


Figure 1.1 Organizing outline

CHAPTER 2

STATE OF THE ART

2.1 INTRODUCTION

The water tanks are very common structures due to the important role they play such as the supply of drinking water to populations. However, reviewing the state of knowledge reflects that the number of standards and publications devoted to these structures is lower than for other structural typologies, such as bridges and buildings. The lack of standards and specific national recommendations for reservoirs causes a situation of confusion for those technicians who want to address their calculation.

The first part of the chapter focuses on describing the different typologies and general concepts relating to water tanks, so that a general knowledge of the subject is addressed. Then, an introduction to the sustainability concept is addressed, as well as the tools and methodologies existed to assess and quantify the sustainability of the structure designed.

In the realization of this chapter and this collection of the general knowledge existed in the studied subject, several studies have been checked (Anchor 1992; Canales and Taibilla n.d.; Dilger 2000; González G. Zabaleta 1986; Mosley, Bungey, and Hulse 2007; Pozo 1967), as well as guides fully dedicated to the subject, which will be mentioned through the present chapter.

2.2 WATER TANKS, TYPOLOGIES AND GENERAL CONCEPTS

A water tanks must guarantee quality and quantity of service. Besides the potability of drinking water, you have to ensure the supply of water continuously and with minimal pressure. In the distribution network, while the pipes are the primarily responsible for transport, deposits act as regulatory elements.

Therefore, we can define a water tank as a structure suitable for containing a certain volume of water, with additional facilities to meet precise flow regulation functions, or both cargo and service security.

2.2.1 Tanks Typologies

Water tanks can be groups and classified according to several aspects (AEAS 1990; Anchor 1992; CEDEX 2010; Hernández 2000). In this section we will described the main different tank's that exist depending on the different aspects that we can take into account in order to classify them.

In the figure below there is a description of the different tanks that we can find according to several different aspects.

Table 2.1 Tanks Typologies

Tanks Typologies	
Classifying criteria	**Typologies**
Position on the field	• Buried • Partially buried • Superficial • Elevated
Function	• Flow controllers • Pressure regulators • Security tanks • Mixed
Relation with the network	• Top, Header or Serial Tanks • Tail, equilibrium, terminals or Shunt Tanks
Implementation process	• Constructed in situ • Prefabricated
Geometry	• Binocular forms: Rectangular • Developed forms: Cylindrical

According to their position on the field

Tanks can be buried, partially buried, surface or elevated. Choosing one or other generally depends on facts such as the geology of the area, its topography, hydraulic dimensions requiring grid and the environmental impact. The different configurations according to their position on the field are shown in Figure 2.1.

Buried Tanks

Buried water tanks are completely built under the ground level. They are preferably used when the ground has a suitable height for the operation of the distribution network and the excavation is simple. In case this typology, it is extremely important to prevent its flotation. Two existing methods to prevent it are adding additional dead weight to the tank, or provision of a heel (Anchor, 1992). As advantages there may be mentioned the following: temperature conservation, adaptation to the environment, or the use of cover for uses other than those related to the operation, provided they are compatible. On the other hand, this typology requires major excavations, both for the excavation itself and for the tank facility network connection, difficulty the control of possible leaks, and possible contamination.

Partially Buried Tanks

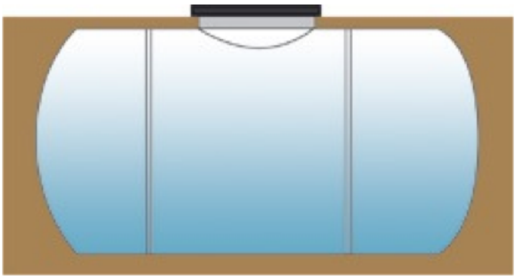
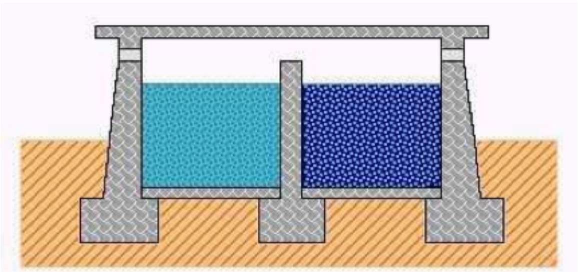
Partially Buried Tanks are those with a part of their structure built under the ground level and another part above it. They are preferably used when the topographical height above the feed point is enough and the ground also presents an average digging difficulty. They are also used when it's needed on slopes where a buried solution would involve extensive excavation with strong slopes.

Surface Water Tanks

The surface tanks are those built and supported directly on the ground level usually used when the soil is hard or when losing height is not convenient. They usually present a low resistance against the influence of the ambient temperature, but are easier to monitor and maintain, and the installation and maintenance of the inlet, outlet and drains are easier and cheaper than the tanks described above.

Elevated Water Tanks

Elevated tanks are those above the ground level and supported by a structure. Usually have lower capacities than the other types due to structural reasons (Hernández 2000). This typology is used when you can't find an appropriate height to place a deposit buried, partially buried or surface.

a)  b) 

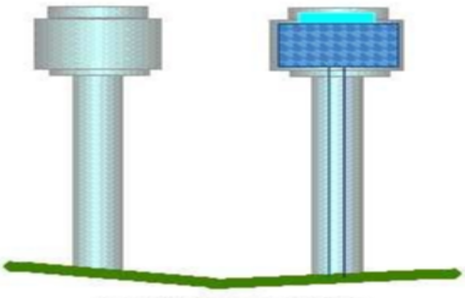
c)  d) 

Figure 2.1 Tanks classification according to their position on the field: a) Buried tanks; b) Partially buried tanks; c) Surface tanks; d) Elevated tanks.

According to their function

According to their function, tanks can be flow controllers, pressure regulators, security tanks or mixed (AWWA 1995).

Flow regulators tanks are those may have very different volumes and serve to offset a given time contribution flows and consumption. The pressure regulator tanks are built ensure the minimum pressure at each point in the distribution network. The security tanks are the ones that provide the necessary volumes of water in case of emergencies are the security tanks. Finally the Mixed Tanks are those that allow to have at least two of the different functions described above.

According to their relationship with the network

In this case we can describe two different types of deposits (INTEMAC, 2012):

- Top, Header or Serial Tanks: Those are also called overhead or feeders, as they process all delivery rate before it enters in the distribution system.
- Tail, equilibrium, terminals or Shunt Tanks: These tanks can only supply an area, and they may be located on the edge of the network in order to receive only the excess water or to regulate the pressure in times of high consumption.

According to the implementation process

The implementation process of a tank may be in situ or prefabricated. On the one hand, tanks constructed in situ usually require structural concrete (both reinforced and prestressed), although they may take other materials as well, such as bricks or stainless steel.

On the other hand, prefabricated tanks are usually constructed of steel, cast iron, concrete and plastic. The utility of these tanks is restricted to small claims such as small towns, farms and factories. The usefulness of prefabricated plastic tanks can also be extended to temporary storage of low capacity to run tanks' renovation or expansion (CEDEX 2010; Hernández 2000).

According to their geometry

- Binocular Tanks: The most common form is rectangular, but they can also take other forms such as hexagons, octagons. Rectangular floor is the most common and desirable if a future expansion is expected somehow, since one side will remain as partition and that way enlargement will be easy and inexpensive.

- Developable Forms: The most used form in tanks are cylindrical and tapered, although it's main disadvantage is having to resort to curved formworks that are more expensive than regular formworks.

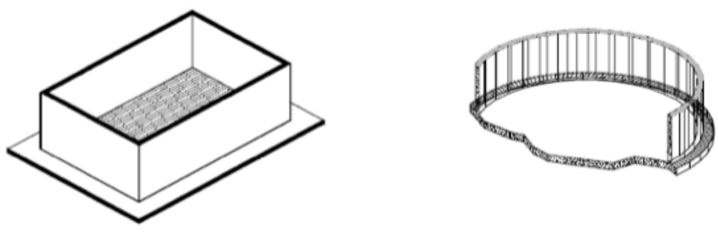


Figure 2.2 Rectangular and Cylindrical Tank's plant

2.2.2 General concepts

As we described above, water tanks are structures designed to contain a volume of water for a certain period of time, which states that the following conditions must be met (Anchor 1992; CEDEX 2010; González G. Zabaleta 1986; Pozo 1967):

- The design, constructions and operation should prevent contamination or other harmful physical, chemical or biological change to the water quality.
- Must meet the needs expressed and have the ability to do so accurately.
- Must be properly integrated into the water supply system
- Provide all necessary components (with appropriate characteristics)
- Your approach should ensure exploitation and maintenance.

Location of the Tank

Choosing the most suitable site for tanks should be obtained after evaluating certain factors such the ones that follow (AWWA 1995, Hernandez 2000):

- The water can reach the tank by gravity or by pumping. The choice between one route and another depends on the difference in level between the source and the tank's location, being always preferable that the transport takes place by gravity.
- The tank must be high enough to ensure at all times and at all points of the network enough pressure. Moreover, this pressure must be uniform throughout the area supplied.
- The foundation must adapt to the land on which it sits, so geotechnical and geomorphological studies must be performed in order to avoid cracks that affect the tank's sealing.
- Take into consideration the tank's environment and assess the environmental and visual impact that the structure may cause.
- Buried or Partially buried water tanks must be located above the water runoff or groundwater. At the same time, any kind of tanks must be located above the level of sewage, always being covered and fitted with a drain to a complete, drain cleaning and disinfection.
- Urban planning should be taken into account, as it will provide essential information regarding the various land uses, future urban development and the possible projected applications.

The point of location of a deposit must be placed so that the distribution network is as economical as possible and the maximum uniformity of pressure throughout the area supplied is elicited. This is achieved by placing the tank in the centroid of the distribution network. However, the altitude depend on whether it is a feeder or equilibrium tank, the best approach to locate on height a distribution tank must refer to the static head by establishing a minimum and maximum level for its location:

- Minimal height: ensures minimal network loads (usually between 0,2 and 0,4 MPa) with a minimum of 10m, in the most unfavorable position, on the roof of the structure to provide.
- Maximum height: does not result static pressures greater than 0,6 MPa in the pressures network, in order to avoid manage.

The complexity in fulfilling all the conditions mentioned above leads to built several tanks in strategic areas in those cities that have large slopes. In general, and depending on the configuration of the area that must be supplied, we can have these different situations:

For flat cities, if the urban layout allows it, the most practical solution is to build an elevated tank in the center. In order to guarantee the necessary amount of water that must be supplied, a possible solution is a regulating tank adjacent to the elevated.

In cases which the populations extends on both sides in a trough, it would be advisable to have a load compensator tanks on the opposite side, at the end of the driving in order to avoid drops in pressure in the network.

If a pipe section by gravity, a buffer tank at the end of follow the drive this driving must be provided with such a volume that ensures control according to daily flows supplied and drained. In cities with longitudinal development it may be convenient to build two reservoirs, one in head (feeder) and another queue (equilibrium). A line that demonstrates supply to the population will connect both tanks.

Geometry of the Tank

The geometric form adopted in the tank's project will affect directly on various aspects such as the economic cost, functionality and installation, construction difficulty, aesthetics, and the decision will depend on many factors like the location, its use or the available resources for the implementation.

The best configuration in order to obtain an optimal tank is the one that for a given height and volume, gets the minimum perimeter, which translates in an optimization of the materials. In most of the cases, that is achieved through a cylindrical geometry configuration, as itst geometry allows a grater optimization of the materials used by getting the minimum perimeter with a given height and volume (CEDEX, 2010).

The main advantage of the rectangular geometry is that they are easier to apply a future amendment, so if a future expansion is expected, the solution is leaving one side of the tank as partition. That is not possible with the cylindrical configuration due to their expensive curved forms required, that raises the cost of the work.

In general, for simple tanks without internal compartments, the most suitable geometry for both points of view, the structural and the construction, is the cylindrical form (Anchor 1992; CEDEX 2010; Pozo 1967). Not only optimizes the storage volume, but induces a proper distribution of stresses, allowing a relatively simple implementation. The cylindrical geometry is hardly compatible with the internal compartments because if more cameras are needed for the proper performance of the tank, in the case of cylindrical tanks is preferable to build a new separate tank due to the high cost of the necessary formwork for its implementation.

However, when it comes to surface tanks with a significant size, or several with one or more compartments, but with the expectation of expanding in the future, it is recommended to choose the rectangular shape. In general, the most economical solution, simpler and easier to run is opting for straight walls of constant thickness (above 30 cm).

Capacity of the Tank

In a village is necessary the installation of a tank that allows flexibility in the consumption flow, as it is constantly variable. Thus, the minimum capacity of a tank is the one that allows storing the excess water when the flow rate of consumption is less than the supply and providing the difference between them otherwise. In turn, the tank must also cover other care of great importance in the service such as providing a supply of water in case of fire and addressing the needs of the population in case of breakdowns or repairs that involve cuts in the supplying of the flow. Therefore, the average capacity of a tank is the required to deal with, prudential manner, the requirements mentioned above. Finally, the maximum capacity of a tank is the one that covers extraordinary risks caused by serious malfunction.

Whenever we refer to the capacity of a tank we mean its useful capacity, the water should not be taken near the bottom of the tank due to the possibility of sediment accumulation. To determine the minimum capacity of a tank, is necessary to have reliable data on the change in consumption during the day of maximum flow, stating whether the flow continuously and smoothly pours during 24 hours by taking the water from springs, or only for a certain number of hours by pumping.

After all described above, we can define the capacity as the minimum volume enough to balance the supply and consumption over 24 hours. However, it is recommended a tank's volume equal to the consumption of 24 hours in the case of large populations or 48 hours for the smaller ones in order to guarantee the supply in case of failure in the power system with the above mentioned reserve volume in case of fire. In any case, the capability should never fall below the required to cover the 12-hour consumption. As a guide, the following table indicates which should be the capacity of a tanks depending on the number of inhabitants in the town, being C the expected average daily maximum consumption day in the period of tank design.

Table 2.2 Tank capacity based on the number of inhabitants (CEDEX, 2010)

Inhabitants	Capacity
< 6000	C
6000 – 12000	4/3 C
12000- 250000	C
> 250000	C/2

Water level height of the tank

Excessive height of water in the reservoir has a number of drawbacks, such as the need resistance of the walls is increased, more ease of leakage as a result of increased pressure, complicates cleaning and causes variations during operation excessive pressure in the distribution.

These factors mean that, normally, a maximum draft of 7 meters is taken in large tanks (with certain exceptions), the latter being comprised between 3 and 6 meters for the small and medium. The specified height is understood to mean, for screeds must have inclinations of some importance to drains.

As a guide, the following table indicates which should be the water level height in the tanks depending on the volume that can contain.

Table 2.3 Tank water level height based on the volume (CEDEX, 2010)

Volume (m^3)	Water level height (m)
< 500	3 – 4
500 – 10000	4 – 5
> 10000	5 – 7

2.3 SUSTAINABILITY

The concept of sustainable development has evolved in recent decades to be paramount in decisions being made today in the developed world. The definition of the concept sustainability given by the UN in 1987 indicates "meet the present needs without compromising the ability of future generations to meet their needs". This definition poses significant challenges to the construction industry, and to the materials in particular.

Sustainability is a global concept, not specific to concrete structures, which requires a series of environmental criteria to be met, in addition to other economic and social criteria. The contribution to sustainability of concrete structures therefore depends on meeting criteria such as the rational use of energy (both in the manufacture of construction products and in the execution of structures), use of renewable resources, use of recycled products and minimization of the impacts on nature as a result of the execution, and also creation of healthy work areas.

2.3.1 Tools to assess the impacts of a structure

During this past decades the concept of sustainable development has evolved to be paramount in decisions being made today in the developed world. Nowadays, in the construction sector, in the planning decisions many actors and parts are involved or should be heard as the decision taken affects them directly or indirectly.

For technicians, applying sustainable criteria during the past decades has been a real challenge without a quantitative and objective support to assess the sustainability of a solution. Luckily, now there are several tools that provide strategies in order to encourage a sustainable development in the construction projects. The main limitation is that sustainability includes many points of view that should be harmonized in order to reach a common goal.

Nowadays, in engineering, an important tool in obtaining detailed information in order to apply sustainable criteria in the decision making process is the Life Cycle Assessment (LCA).

2.4 IMPLEMENTATION PROCCESS AND ITS SUSTAINABLE DEVELOPMENT

The study performed in this work is focused on reinforced concrete tanks built onsite, and the aim of this section is to summarize some aspects that characterize this construction typology and to mention main required aspects to take into account in order to contribute to a sustainable development of the tanks' construction. In Figure 2.4 the main stages to follow in order to build the reservoir on site are shown.

One of the main characteristics of the constructions built onsite is that they are normally carried out in open areas where the climatic conditions to which the structure is exposed are not controlled in any way.

Given this situation, the prevailing choice is in favor of the implementation of procedures developed to adequately control the generation of all the potential impacts on environment resulting from the execution of the structure, such as the waste generation, including all kinds of emissions, produced noises or other similar environmental impacts which contribute to not providing a sustainable construction.

Another important aspect to consider in this execution typology is that generally, as the construction fences are usually overtopping, providing a grained access control to the work for people and goods is not possible. The entire responsibility for this control rests in the documentary checks carried out during the Quality and Safety inspections, and in the documents (invoices, certificates of manufacturing tests and others) from the providers and laboratories.

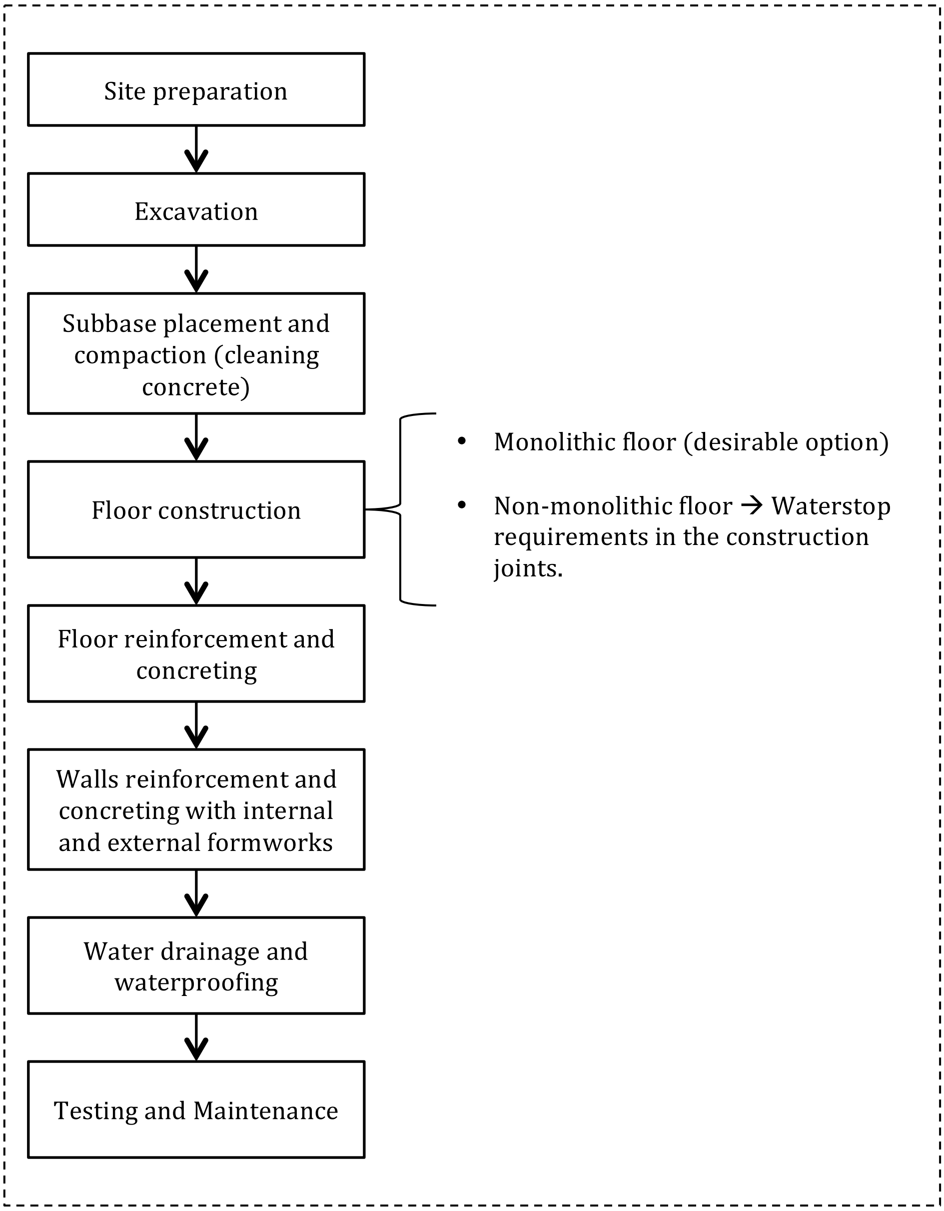


Figure 2.3 Implementation procedure of a standard tank

In a structure built onsite, the three main areas subjected to an environmental load during the execution procedure are the implementation itself, the materials transport and the materials used in the structure.

Mainly, the aspects that provide an environmental impact in the execution of the work are earthworks, dust generation, noise, emissions and waste. Within the transport of materials are the energy consumption, volatile emissions, deterioration of the road network and public nuisances. Finally, according to the materials, the most important aspects are those related to their implementation, maintenance and future demolition and recycling. The water is also a factor to consider given its high consumption during the following phases: concrete manufacturing, curing and cleaning of the tanks and utensils.

Materials transport

The transport of materials on site is an important factor to assess the environmental impact generated by the structure. Despite of the transport of big prefabricated elements, the transportation of concrete to the work is an ordinary and standardized transport, which can flow smoothly through road networks, without cutting the traffics or being carried at nighttime.

The transport phase includes several materials and equipment, such as the ones that are explained below. During the transport of the concrete from the manufacturing plant different concrete tanks of varying capacities are used, being the most common the ones with a 6 m^3.

Transporting of the proper equipment to develop the structure it is also an important factor. They come from the storage or previous destination, such as formwork, scaffolding, vibrating equipment, and elements and ancillary products. Also mentioning the transportation of the steel required to the reinforcements must be taken into account.

<u>Surplus materials and waste generated at the construction onsite</u>

During the implementation process of a structure onsite the main surplus materials and waste generated include all listed below:

- Hardened concrete accidentally spilled.
- Debris mass or reinforced concrete obtained by demolition or by cutting specific tools, coring, etc.
- Blow debris from ceramic materials, soils treated with lime or cement, plasters and tiles agglomerates.
- Corrugated steel from trimmings cuts or waste material.
- Wood used in construction formwork, not included the one in modular systems.
- Fresh concrete remains of fresh concrete accidentally pour and debris from washing concrete tanks after emptying them.
- Bentonite sludge usually used in the execution of walls or piles, jet grouting and similar.
- Oils, diesel fuels and other fluids from the hydraulic systems of machinery.
- Materials used in plaster ceilings or linings.
- Porexpanes, extruded polystyrene, mineral wool and other insulation.
- Various metal residues strapping, bits of profiles, pipes, etc.
- Nonconforming products intended to be withdrawn by the manufacturer.
- Inert waste land type, rocks, mud and other products of excavation, although many states do not consider them as waste.
- Several non-hazardous wastes: plastic and paper packaging, pieces of pipe, waterproofing fabrics and plastics, etc.
- Other hazardous waste or require special handling: demolition of roofs and pipes with asbestos, hazardous contaminated soil, solid waste found in excavations, etc.
- Paint cans, additives, etc.

Regarding to the waste management of those materials mentioned, the so-called European Waste Hierarchy must be applied, which includes the following phases:

- Prevention
- Preparation for the use
- Recycling
- Other valuation, including energy recovery
- Elimination

As a result, the first strategy that arises in this construction typology is always to reduce the volumes of waste generated. However, it should be pointed that in this case such wasting management in conditioned by the typo of work and its magnitude associated. Unlike in a prefabricated elements construction, the well produced at the construction onsite is implemented on a fixed physical environment and rarely or almost never transportable, whereby the product concept requires a high degree of abstraction.

Summarizing, the main goal of applying a sustainable development in a concrete structure built through an onsite construction is to decrease the amount of waste generated from the concrete manufacture, promoting the maximum possible attainable recycling of any waste whose generation is unavoidable, and the reduction of environmental impacts during the laying of the concrete.

2.5 LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

Life Cycle Assessment (LCA) is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment. Along with the Life Cycle Thinking (LCT), it scientifically approach decision support related to Sustainable Consumption and Production (SCP).

From the environmental point of view, it is the best tool to evaluate different materials, taking into account the complete cycle: from the extraction of resources, throughout the manufacturing and maintenance process, to the disposal of remaining waste, providing a global assessment of the structure. Therefore, it is a quantitative method that allows not only to cover the entire service life of the structure, including its deconstruction, but it is couched in terms that can integrate such evaluation with the environment of the structure.

The Life Cycle Assessment can assist in:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Informing decision-makers in industry, government or non-government organizations. For example, to provide a strategic planning, priority setting, product or process design or redesign.
- The selection of relevant indicators of environmental performance, including measurement techniques, and
- Provide marketing strategies. For example, implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

Figure 2.4 Life cycle assessment of a product

2.5.1 LCA Framework

To provide guidance for consistent and quality assured LCA data and studies there is series of technical documents recalled in the International Reference Life Cycle Data System (ILCD) Handbook and Data Network.

The ISO 14040 and 14044 standards provide the indispensable framework for LCA. In the figure that follows below, the LCA framework detailing its different phases as a introduction that will be described throughout the present section.

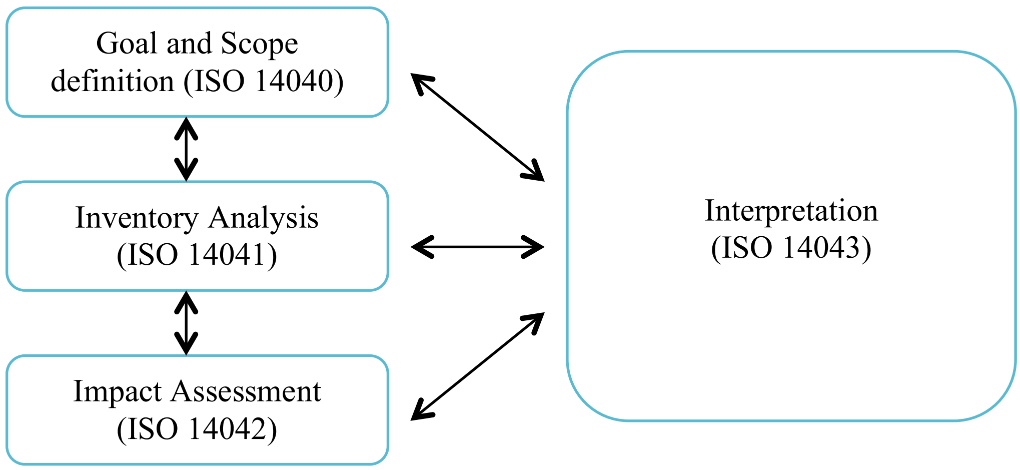


Figure 2.5 Phases of the Lyfe Cycle Assessment (ISO 14040)

Even though the ISO 14040 provides the indispensable guide and principles to perform an LCA process, as mentioned in Figure 2.5, other ISO standards establish specific basis for each of the phases integrated in the LCA framework, some of them still in approving phase for becoming international standards.

<u>Goal and Scope</u>

The goal and scope definition of the system is the first phase in the Life Cycle Assessment methodology. The scope of a Life cycle assessment shall clearly specify the functions or performance characteristics of the system being studied. An important decision in this first phase is to define the functional unit of the system (Fu). One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized in a mathematical sense.

Comparisons between systems shall be made on the basis of the same functions, quantified by the same functional units in the form of their reference flows. If additional functions of any of the systems are not taken into account in the comparison of functional units, then these omissions shall be explained and documented.

In the scope definition the object of the study must be identified and defined in detail. After that, the requirements on methodology, quality, reporting and review in accordance with the goal of the study, the decision-context, the intended applications, and the addressees of the results shall be defined as well. (ILCD Handbook, 2010).

In order to define which parts of the life cycle and which processes belong to the analyzed system, a system boundary must be set. The factors that must be taken into account in order to decide the boundaries of the study are: the goal of the study and the audience, the main hypothesis and the exclusion criteria.

In the picture below is an example of the system boundaries of a drinking water supply construction phase:

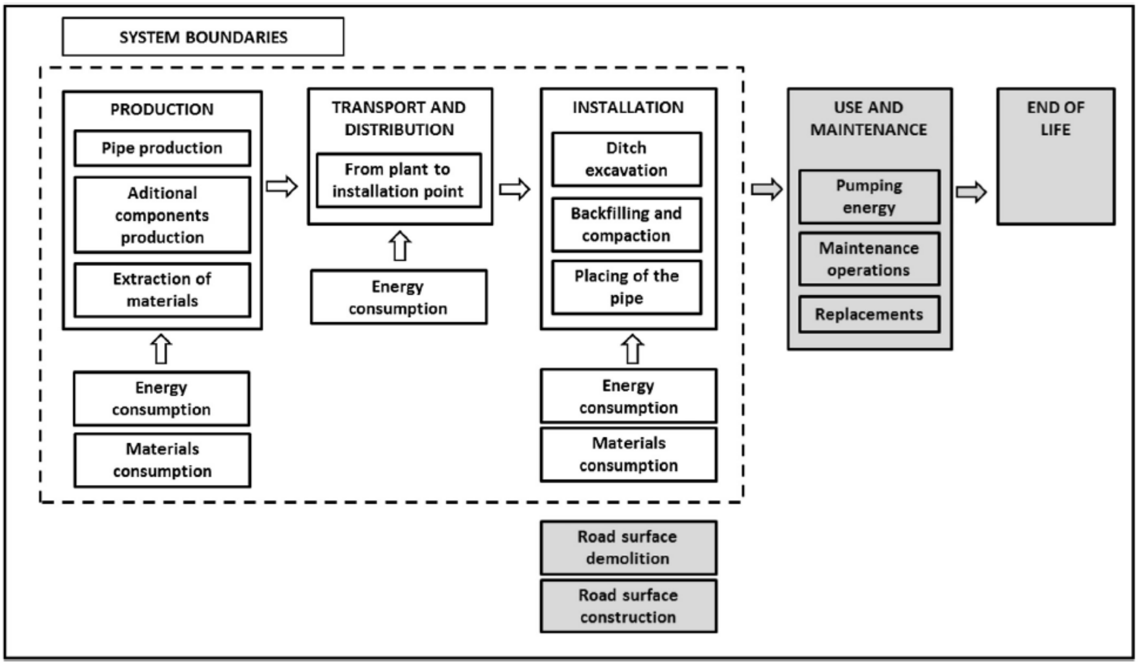


Figure 2.6 System boundaries of a drinking water supply

Life Cycle Inventory

This stage includes the data collection and the calculation procedures to identify and quantify all the effects on the environment. Some examples of environmental burdens are: resources and energy consumption, hazardous gaseous emissions, leachates, solid wastes, noises, radiations, heat, etc.

There are two types of data: primary data (foreground) and secondary data (background) (ILCD Handbook, 2010).

- **Primary data:** such as the producers of good and operators of processes and services, as well as their associations.
- **Secondary data:** are generic and can be found in the literature. Englobes the required database or statistical data to provide an approximate value for an unknown variable.

Impact Assessment

The inventory results of a LCA usually contain hundreds of different emissions and resource extraction parameters. Thus, these emissions and extractions must be classified into the impact categories -which represent environmental issues of concern- that have must be previously chosen.

Once the LCI results are assigned to these impact categories, it is necessary to convert the emissions of each impact category to the impact category indicator. For doing so, it is necessary to define characterization factors (which reflect the relative contribution of the emission to the impact category indicator) for each emission.

In the picture below is an example of an impact assessment performance:

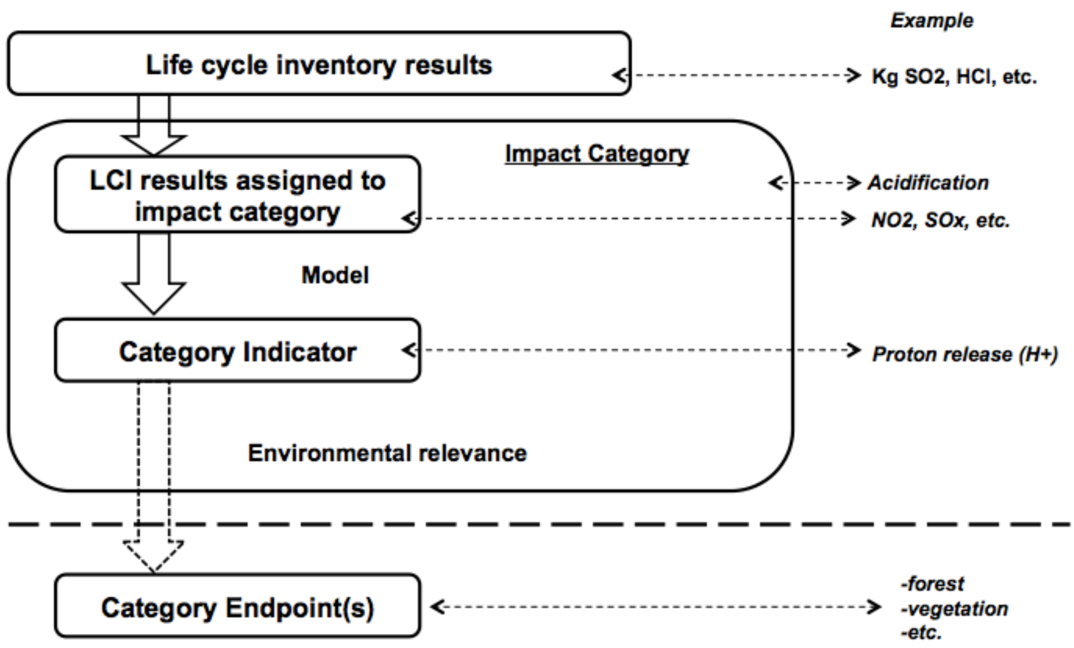


Figure 2.7 Impact assessment example

As shown in the Figure 2.7 the impact assessment includes 4 steps to follow (ILCD Handbook, 2010): (1) classification, (2) characterization, (3) normalization and (4) weighting.

Impact Categories

The impact assessment stage allows the connection between the inventory of our system and the environmental impacts related with certain specific environmental issues. The results expressed in midpoint indicators are more difficult to analyze, since more categories are involved. However, they involve less uncertainty than endpoint indicators and are scientifically more accepted.

Interpretation

Integrating the outcome of the other elements of the interpretation phase, and drawing on the main findings from the earlier phases of the LCA, the final element of the interpretations is to set conclusions and identify limitations of the LCA, as well as developing recommendations for the intended audience in accordance with the goal definition and the intended applications of the results.

2.6.2 LCA tools and databases

During the last years several tools have been developed to make easier the LCA calculations. The inventory of the system is introduced in the tool in order to obtain the environmental impacts (it provides the results for midpoints or endpoints indicators).Examples of software used to develop theses assessments:

- **SimaPro:** (Pré Consultants, the Netherlands) is the program most used to develop LCA analysis.
- **GaBi 4:** (IKP, Germany) computational program with engineering approach.
- **TEAM™:** (Ecobilan group, UK) powerful and flexible program for LCA analysis.
- **Umberto**: (IFEU, Germany) it is a very powerful and flexible to apply the LCA and the analysis of the materials and energy within the industry.
- **LCAiT - CIT Ekologik:** (Chalmers, Sweden) program to apply the LCA with a graphical interface.

The LCA softwares use databases containing environmental information for several elements. SimaPro can use several databases (BUWAL, ecoinvent, ELCD, etc.), the most broadly used of which is ecoinvent:

- **ecoinvent v2.2** (Swiss) The Swiss centre for Life Cycle Inventories has combined and extended different LCI databases. Mainly for Swiss and Western European conditions. Contains datasets of several sectors (2010).

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CHAPTER 3

PERFORMANCE OF THE CALCULATION PROGRAM

3.1 INTRODUCTION

Concrete is a malleable material with good mechanical and durability properties. Though it high strains and compressive stresses, it provides a very low tensile strength. The solution is to combine the concrete and the steel through passive reinforcements, which will withstand the tensile stresses generated in the structure. The reinforcements endow the structure greater ductility, which allows structures to deform significantly before reaching the total collapse.

The program associated with this thesis has been developed in order to solve the calculations related to the designing of reinforced concrete tanks. The final result obtained by the program is the amount of material (volumes of land, concrete and armor) for the construction of a reinforced concrete tank.

From the tank's geometry, the volume of land and concrete required is obtained, but in the case of the amount of steel needed for the reinforcements there is more information required. The Analysis of reinforced concrete slabs and walls is a complex finite element exercise that will be resolved thanks to the practices suggested by the EHE-08, explained in section 3.4, and alongside what is presented through the other sections, corresponding to the different procedures according to each typology evaluated.

In this chapter the first topic addressed is the wall calculation of rectangular reinforcement concrete walls. It is explained the way to evaluate the bending, shear and tensile efforts combined with the cracking to eventually be able to have the proper armor for the tank designed.

Then the cylindrical tanks design method is explained. In this case the evaluation of the effort of the wall is more complex than the rectangular case. Since we are facing a circular cylindrical sheet, where the solution of the displacement field and efforts leads the need to find the value of four integration constants that depend in the boundary conditions of the tank. In previous study (Riba et al., 2006; Orbe et al., 2013), the solutions to give the maximum facilities enough conditions to simplify the calculation. With the tools provided and the proper assumptions made, the solution to this typology will be given.

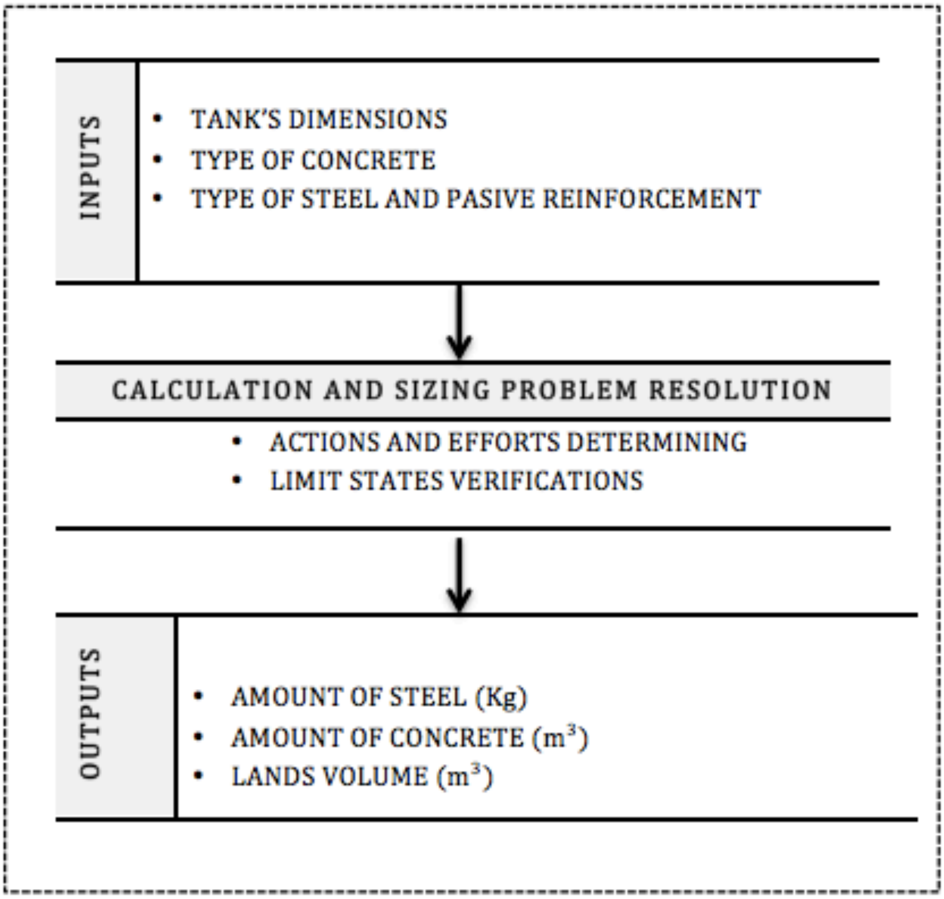


Figure 3.1 Flowchart of the general structural design performance

3.2 RECTANGULAR REINFORCED CONCRETE TANKS

Figure 3.2 shows a flowchart of the structural design performance of rectangular reinforced concrete tanks, where the steps and stages analyzed are described in the followed order.

3.2.1 Preliminary Data

The first page of the program shows the preliminary data required to initiate the tanks' analysis. The inputs needed to solve the problem are mainly the height of land, which determines the deposit position relative to the ground (buried, partially buried or surface), the water height, and the dimensions of the walls as well as the thickness of the walls.

The data on the type of concrete is also listed. From this information we are able to extract the following values: f_{ck}, f_{cd}, f_{ctm}. Being f_{ck} the characteristic compressive strength of the concrete, f_{cd} the design compressive strength of the concrete and f_{ctm} the mean compressive strength at the age of 28 days, and which values are the ones that follows (in $\frac{\mathrm{N}}{\mathrm{mm}^2}$),

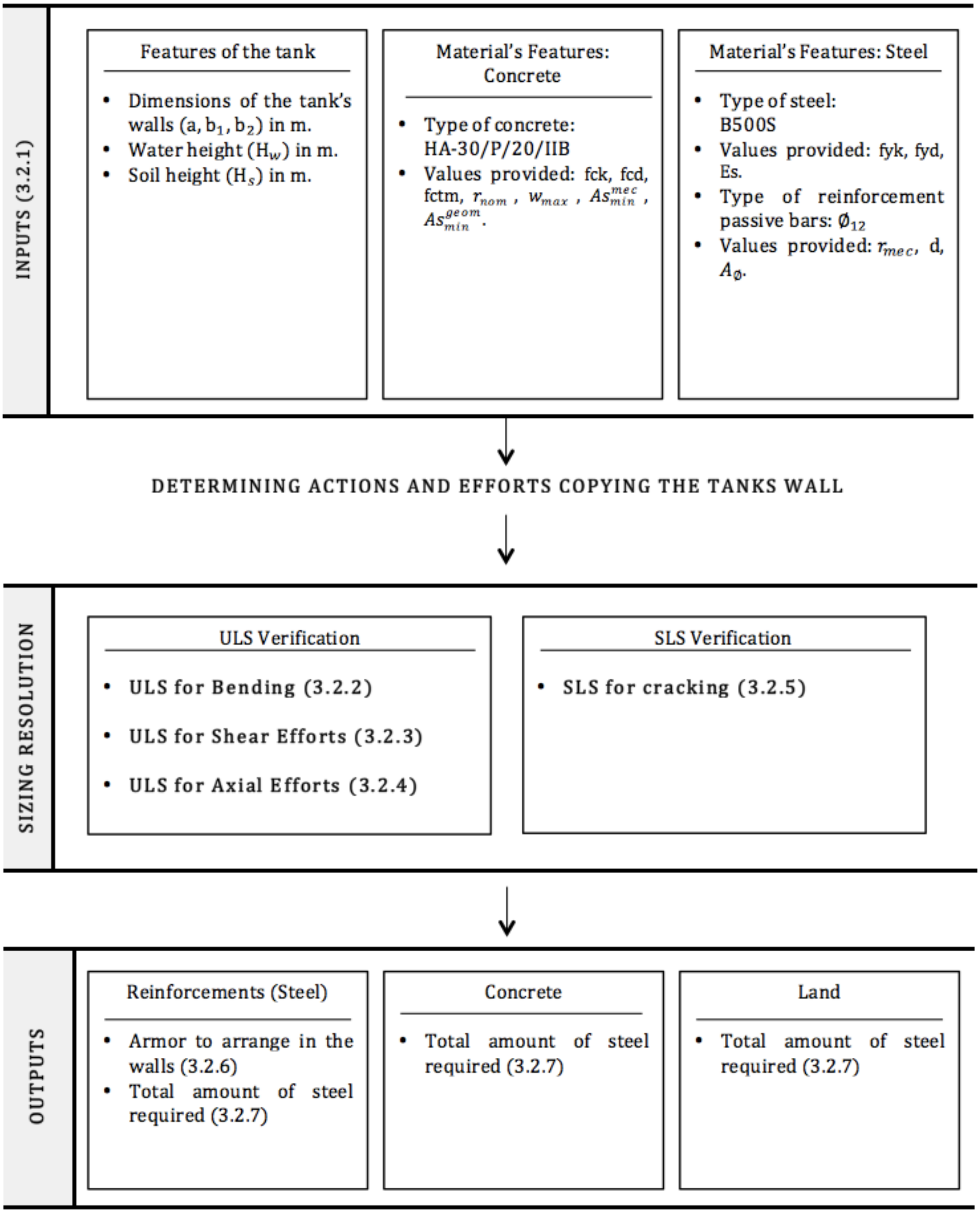


Figure 3.2 Flowchart of the structural design of Rectangular reinforced concrete tanks

$$f_{cd} = \frac{f_{ck}}{\gamma_s} \quad [3.1]$$

$$f_{ctm} = 0{,}3\sqrt[3]{{f_{ck}}^2} \quad [3.2]$$

And from the type of environment to which the concrete is exposed, with that value and the service lifetime of the structure we know what the minimum and nominal covers that are required to fulfill the service life demands.

In turn, from the type of steel used in the reinforcements, the f_{yk} and f_{yd} values are known; being Es the modulus of longitudinal strain of steel with the value of 200000 $\frac{\mathrm{N}}{\mathrm{mm}^2}$, f_{yk} the characteristic yield stress of the steel and fyd the design yield stress of the steel, which value is the one that follows (in $\frac{\mathrm{N}}{\mathrm{mm}^2}$),

$$f_{yd} = \frac{f_{yk}}{\gamma_s} \quad [3.3]$$

In which γ_s is the partial safety coefficient applied in order to study the Ultimate Limit State in a persistent situation.

Setting the type of environment in which the deposit will be exposed, prior to the calculation, we set the conditions for maximum allowable crack opening and the values of minimum armor ratios, mechanical and geometric in order to avoid problems of cracking or brittle fracture. The criterion followed is explained in detail in the previous chapter, where the procedures established by the actual code are discussed.

Finally, the types of reinforcing bars that will be used in the sizing are fixed. From the bar diameter to use, the value of the mechanical reinforcement cover and effective depth of the section is fixed, both values needed to solve the problem of sizing.

With all the previous data described above, it is possible to start with the problem resolution. The second page of the program details the loads combination acting on the tank, mainly in function of hydrostatic pressure and earth pressure, and calculates the respective efforts to resolve all different parts that takes part into the resolution of this problem. The criteria followed to calculate each of the efforts are discussed below in each corresponding section.

3.2.2 Calculation of the wall in ultimate state for bending

3.2.2.1 Determination of the design bending moment

As assumption in order to simplify the problem, we will treat the tank's wall as a plate fixed at three points, on the floor and the two sidewalls, and with the upper edge free, as shown in Figure 3.3. Thus, bending moments appear in the vertical and horizontal directions, as shows Figure 3.4 and to solve its laws propose to use the method followed by a previous study (Riba et al, 2006) based on the tables of Bares' plates (1970). The sections of the table used in the program operation and their associated hypotheses are explained below.

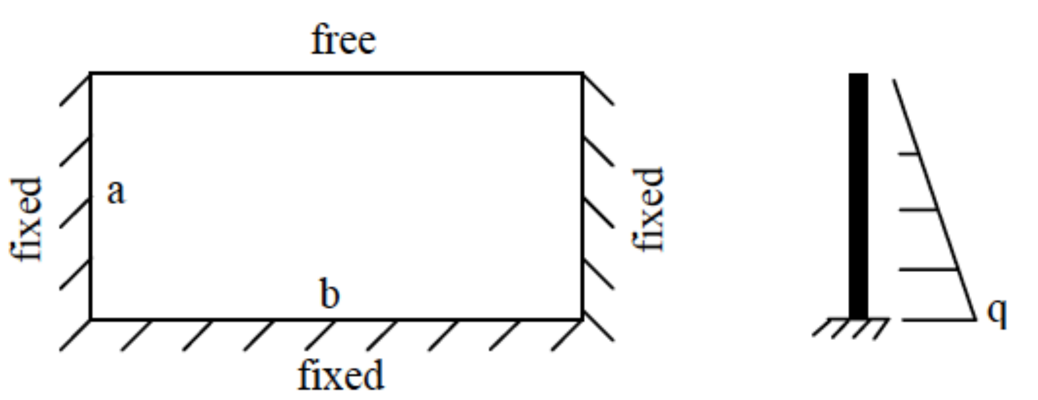


Figure 3.3 Assumption to treat and solve the tank's wall

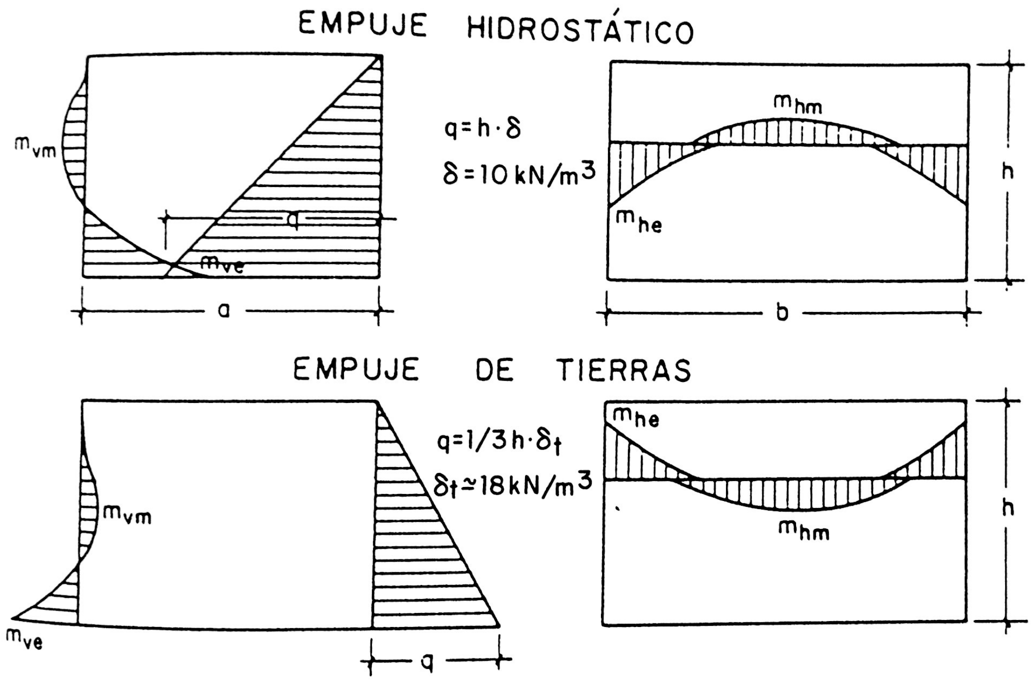


Figure 3.4 Bending moment laws generated in rectangular tank (Hormigón Armado)

To resolve the first combination of actions, C1: 1,35x(Buoyancy), described in section 3.4.4, the values of table 3.4, which shows the values provided by Richard Barés (1970) adapted to the water tank case, will be used, and we will proceed as follows:

- Find the value of γ depending on the dimensions of the plate.
- Calculate the value of the maximum factored load at the bottom:

$$q_{wd} = \gamma_f \cdot q_w = 1{,}35 \cdot \gamma_w \cdot H_w \quad [3.4]$$

- Search the horizontal bending moments in the table, both negative maximum (M_{x1d}, M_{x7d}) as the positive maximum (M_{x6d}, M_{x10d}).
- Search the vertical bending moments in the table, both negative maximum (M_{y28d}) and the positive maximum los (M_{y14d}, M_{y18d}).

To solve the second combination of actions C2: 1,50x(Soil pressure), we will use the tables of Bars, depending on the height of land, which, as previously indicated, differences the type of tank to evaluate, and proceed as in the previous case, but where the maximum value of the load in the bottom will be:

$$q_{sd} = \gamma_s \cdot q_s = 1{,}5 \cdot \gamma_s \cdot tan^2(45 - {}^{\emptyset}/_{2})H_s \qquad [3.5]$$

Once the values of the bending moments in the different sections are known, we can assess which are the design moments of each section to size. Table 3.1 shows the nomenclature of the different reinforcement to arrange in every section of the wall.

Table 3.1 Armor nomenclature and distribution in ULS for bending

FACE OF THE WALL	SECTION	ARMOR REQUIRED (in both sections)
Inner Vertical	• Top • Bottom	Av_1
Outer Vertical	• Top • Bottom	Av_3
Inner Horizontal	• Embedment • Central	Ah_1
Outer Horizontal	• Embedment • Central	Ah_4

For the inner vertical section of the wall, we look for the envelope law of the vertical bending moments on the inner side at the junction of the combinations C1 and C2 (since both combinations can leave part of its law on the inside). Thus, we define the design bending moment (Md) for both the top and bottom of the wall. With this design bending moment the required reinforcement value Av_1 will be evaluated according to the criteria established in the actual code.

For the outer vertical section of the wall, we look for the envelope law of the vertical bending moments on the outer side at the junction of the combinations C1 and C2 (since both combinations can leave part of its law on the outside). Thus, we define the design bending moment (Md) for both the top and bottom of the wall. With this design bending moment the required reinforcement value Av_3 will be evaluated according to the criteria established in the actual code.

In order to find the required reinforcement for bending on the inner horizontal section of the wall, we look for the envelope law of the horizontal bending moments on the inner side at the junction of the combinations C1 and C2 (since both combinations can leave part of its law on the inside). Thus, we define the design bending moment (M_d) for both the embedment and the central section of the wall. With this design bending moment the required reinforcement value Ah_1 will be evaluated according to the criteria established in the actual code.

Finally, for the outer horizontal section of the wall, we look for the envelope law of the horizontal bending moments on the outer side at the junction of the combinations C1 and C2 (since both combinations can leave part of its law on the outside). Thus, we define the design bending moment (M_d) for both the embedment and the central section of the wall. With this design bending moment the required reinforcement value Ah_4 will be evaluated according to the criteria established in the actual code.

3.2.2.2 Calculation of the bending reinforcement

The third page of the software involves the calculation of the reinforcement required for bending stresses. To calculate the required reinforcement to deal with the bending generated in the tanks' walls, in all cases the criteria followed is the one established in the actual code EHE-08, as mentioned above. More precisely, the formulation followed to size the required reinforcement to cope with the bending stresses is the one detailed in the Annex 7 of the current code.

This methodology is aimed to obtain the required reinforcement from the design bending moment established and through the verification of the formulation set by the code.

The first step is to establish whether we are in a situation of ductile or brittle fracture by comparing the design bending moment with the limit bending moment of the section. Knowing that will allow us to establish whether it is required to size the reinforcements exclusively in the tensile area or if the armor is required for both the tensile and the compressive area of the section in order to cope with the stresses generated in the walls.

Above are described the equations used and required as preliminary calculation,

$$U_0 = fcd \cdot b \cdot d \qquad [3.6]$$

$$M_{lim} = 0{,}375 \cdot U_0 \cdot d \qquad [3.7]$$

In which,

d: Effective depth of the section, with value ,

$$d = h - r_{mec} - \frac{\emptyset}{2} \qquad [3.8]$$

b: Unit width of the section.

M_{lim}: Limit bending moment of the section, which determines which kind of fracture will the structure be subjected.

Once the assumption above is established and we know whether the section will suffer a ductile of brittle fracture, through a several formulations the value of the required reinforcement due to calculation will be known.

1. Ductile Fracture $(M_{lim} \geq M_d)$

$$U_{s2} = 0 \qquad [3.9]$$

$$U_{s1} = U_0\left(1 - \sqrt{1 - \frac{2M_d}{U_0 d}}\right) \qquad [3.10]$$

2. Brittle Fracture $(M_{lim} < M_d)$

$$U_{s2} = \frac{M_d - M_{lim}}{d - d'} \qquad [3.11]$$

$$U_{s1} = 0{,}5U_0 + U_{s2} \qquad [3.12]$$

To find the value of the required reinforcement, the formula described as follows shall be met,

$$A_s = \frac{U_s}{f_{yd}} \qquad [3.13]$$

And finally, to set the required design armor, this amount shall be compared to the minimum geometric and mechanical ratios set at the beginning of the problem, as the final amount of armor will be the higher of the three values compared; the strict amount due to calculation ($A_{s,est}$), the minimum geometrical armor ($A_{s,geom}$) and the minimum mechanical reinforcement ($A_{s,mec}$).

3.2.3 Calculation of the wall in ultimate state for shear efforts

The fourth page of the software involves the calculation of the reinforcement required due to the shear efforts generated in the walls.

In order to find the design values of the shear efforts generated in the tanks' walls, the Barés Tables (1970) criteria shown in table 3.4 will be used. In this case, we seek the maximum values for R_{xd} and R_{yd} reactions. With the value of this reactions we will extract the value of the maximum shear effort generated in the tank's wall V_d.

As assumption in order to determine the amount of reinforcement required to cope with the shear efforts, we have taken the approach that the maximum shear effort can be absorbed by the concrete contribution V_{cu}. Thus, nor type of fence or shear reinforcement is required.

Recall that according to EHE-08, the contribution of the concrete to shear efforts is:

$$V_{cu} = \left(0{,}12 \cdot \xi \sqrt[3]{100 \cdot \rho_1 \cdot f_{cv}}\right) \cdot b_o \cdot d \qquad [3.14]$$

In which:

$$\xi = 1 + \sqrt{\frac{200}{d}} \leq 2{,}0 \qquad [3.15]$$

d: Effective depth of the section, with value as sets equation [3.9]
ρ_1: Geometric ratio of the main longitudinal tensioning reinforcement, with value,

$$\rho_1 = \frac{A_s}{b_o \cdot d} \leq 0{,}02 \qquad [3.16]$$

f_{cv}: Effective shear strength of the concrete in N/mm^2 with a value $f_{cv} = f_{ck}$
b_o: Minimum width of the section

The checking procedure to validate the assumption of nor requirement of fence or shear reinforcement is comparing the value of the contribution of the concrete to the shear strength (V_{cu}) with the maximum shear effort generated in the wall (V_d). In order to validate the assumption, the expression that follows must be checked,

$$V_{cu} \geq V_d \quad [3.17]$$

3.2.4 Calculation of the wall in ultimate limit state for axial efforts

In the fifth page of the software the calculation of the reinforcement required due to the axial efforts generated in the walls is performed.

In this case, we have to solve the ultimate limit state for axial efforts, expressed in the combination C3: 1,00x(Buoyancy) described in section 3.4.4. The no factored load application in this action, as discussed in the previous chapter, is due to taking a steel stress value of only σ_s= 100 or 130 N/mm^2. In a simplified manner, it can be assumed that the axial stresses which arise in the walls of the tank due to the buoyancy is:

In the sidewall with dimension a, in accordance with the nomenclature used in the program, the sidewall corresponds to the dimension b_1.

$$N_{apd} = 1{,}00 \cdot \beta_p \cdot \frac{1}{2} \cdot \gamma_w \cdot H_w^2 \cdot b, \quad [3.18]$$

In the sidewall with dimension b, in accordance with the nomenclature used in the program, the sidewall corresponds to the dimension b_2.

$$N_{bpd} = 1{,}00 \cdot \beta_p \cdot \frac{1}{2} \cdot \gamma_w \cdot H_w^2 \cdot a, \quad [3.19]$$

These axial efforts are distributed according to the percentages β_p indicated in the tale presented in Figure 3.5 given by Jiménez Montoya et al (1987). Figure 3.5 shows the distribution coefficient values of tensile stresses in rectangular tanks are described.

In this study the axial efforts are calculated per lineal meter, so we will get one value of the reinforcement required to cope this stresses that later, at the time of distributing the reinforcements in the tank, shall be expressed along the wall dimension. Once we have the value of the axial effort, we can calculate the required reinforcement as proceeds:

$$Ah_3 = \frac{N_{pd}}{\sigma_s \cdot H_w} \quad [3.20]$$

3.2.5 Wall checking under serviceability limit state for cracking

This section, treated in the sixth page of the software, describes the resolution of the serviceability limit state for cracking, and is the fifth page of the software. The problem resolution starts with the expressions according to the combinations C4: 1,00x(Buoyancy) and C5: 1,00x(Soil Pressure), described as the rest of action combinations in section 3.4.4 of the present chapter.

To solve the combination of actions C4: 1,00x(Buoyancy) will use the same horizontal and vertical bending moments that we have found from the combination C1 used in the ultimate state for bending resolution, but in this case, without applying the load increment factor, since in that case, a serviceability limit state is evaluated.

Armadura paralela al lado b	Esfuerzo total			Esfuerzo pared			Esfuerzo fondo	
	$N_b = \frac{a \cdot h^2 \cdot \delta}{2}$			$N_{bp} = \frac{\beta_p \cdot a \cdot h^2 \cdot \delta}{2}$			$N_{bf} = \frac{\beta_f \cdot a \cdot h^2 \cdot \delta}{2}$	
h/a →	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Fondo β_f =	0,80	0,70	0,60	0,54	0,48	0,45	0,42	0,40
Pared β_p =	0,10	0,15	0,20	0,23	0,26	0,275	0,29	0,30
h/b →	0,30	0,40	0,50	0,60	0,70	0,80	0,90	1,00
Armadura paralela al lado a	$N_a = \frac{b \cdot h^2 \cdot \delta}{2}$			$N_{ap} = \frac{\beta_p \cdot b \cdot h^2 \cdot \delta}{2}$			$N_{af} = \frac{\beta_f \cdot b \cdot h^2 \cdot \delta}{2}$	
	Esfuerzo total			Esfuerzo pared			Esfuerzo fondo	

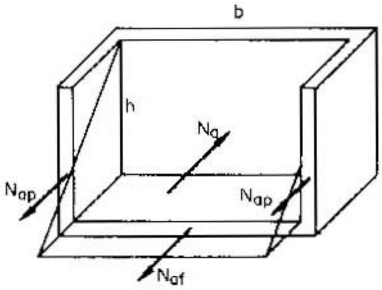


Figure 3.5 Distribution coefficient values of tensile stresses in rectangular tanks (Hormigón Armado)

Similarly, to address the combination of actions C5: 1,00x(Soil pressure) we will use the horizontal and vertical bending moments without applying the load increment factor used to solve the combination C2 from the ultimate state for bending.

Table 3.2 shows the nomenclature of the different reinforcement ratios to arrange in every section of the wall.

For the inner vertical section of the wall, we look for the envelope law of the vertical bending moments on the inner side at the junction of the combinations C4 and C5. The reinforcement provided by the design moment for bending Av_2, must produce a maximum crack opening of $w_k \leq 0{,}2$ or 0,1 mm depending on the cracking criteria adopted.

Table 3.2 Armor nomenclature and distribution in SLS for cracking

FACE OF THE WALL	SECTION	ARMOR REQUIRED (in both sections)	CHECK TO BE MET
Inner Vertical	• Top • Bottom	Av_2 →	$w_k \leq 0{,}2$ or 0,1
Outer Vertical	• Top • Bottom	Av_4 →	$w_k \leq 0{,}2$ or 0,1
Inner Horizontal	• Embedment • Central	Ah_2 →	$w_k \leq 0{,}2$ or 0,1
Outer Horizontal	• Embedment • Central	Ah_5 →	$w_k \leq 0{,}2$ or 0,1

For the outer vertical section of the wall, we look for the envelope law of the vertical bending moments on the outer side at the junction of the combinations C4 and C5. The reinforcement provided by the design moment for bending Av_4, must produce a maximum crack opening of $w_k \leq 0{,}2$ or 0,1 mm depending on the cracking criteria adopted.

In order to find the required reinforcement for the inner horizontal section of the wall, we look for the envelope law of the vertical bending moments on the outer side at the junction of the combinations C4 and C5. The reinforcement provided by the design moment for bending Ah_2, must produce a maximum crack opening of $w_k \leq 0{,}2$ or 0,1 mm depending on the cracking criteria adopted.

Finally, for the outer horizontal section of the wall, we look for the envelope law of the vertical bending moments on the outer side at the junction of the combinations C4 and C5. The reinforcement provided by the design moment for bending Ah_5, must produce a maximum crack opening of $w_k \leq 0{,}2$ or 0,1 mm depending on the cracking criteria adopted.

3.2.5.1 Calculation of the cracking reinforcement

The criterion for evaluating and extracting the value of the required reinforcement to address cracking in the different positions of the tank follows the criteria detailed in the actual code EHE-08. In the case of verifications relating to Cracking Limit State, the effects of actions comprise the tensions in the sections (σ_c) and the crack openings (w_k) that they cause, as applicable. Both σ_c and w_k are calculated from the design actions and the combinations described in the previous section.

As described in the last section of this chapter, in accordance with the current European Code, EHE 08, in order to avoid the appearance of compression cracks, the compressive stresses in the concrete shall satisfy the checking described in equation [3.35]. And for avoiding the cracking due to tension, the verifying criteria set by the code is the one described in equation [3.36].

In which w_k is the characteristic crack opening, calculated in accordance with the formulation presented in the section 3.4.5 in the present chapter, while $w_{máx}$ is the maximum crack opening allowable, also described in section 3.4.5 of the present chapter.

To solve this problem and find the value of the reinforcement required, the procedure is the same as described in the bending sizing section to extract the required armor to cope with the stresses generated in the walls and avoid the appearance of higher cracks than the allowable established in advanced.

In this case, as we are evaluating a serviceability limit state, the design moments selected will be the ones applied in the bending sizing problem but without applying the partial safety factor, as described in section 3.4.4. With the values of the required reinforcements known, we have to proceed verifying the two criteria set by the code and described in equations [3.35] and [3.36] in order to avoid the cracking due to compression and tension stresses.

3.2.6 Amount of armor to arrange in the tank's wall

The last part of the software deals with the calculation of the total amount of steel required in the tank's wall. In table 3.3, the design amount of reinforcement to arrange in every section of the wall is described.

Table 3.3 Amount of armor to arrange in the tank

FACE OF THE WALL	SECTION	ARMOR REQUIRED (in both sections)	ARMOR TO ARRANGE
INNER VERTICAL	Top Bottom	• ULS for bending: Av_1 • SLS for cracking: Av_2 • Minimum geometric armor: Av_{min1} • Minimum mechanical armor: Av_{min2}	$\mathbf{max}\{\boldsymbol{Av_1}\|\boldsymbol{Av_2}\|\boldsymbol{Av_{min1}}\|\boldsymbol{Av_{min2}}\}$
OUTER VERTICAL	Top Bottom	• ULS for bending: Av_3 • SLS for cracking: Av_4 • Minimum geometric armor: Av_{min1} • Minimum mechanical armor: Av_{min2}	$\mathbf{max}\{\boldsymbol{Av_3}\|\boldsymbol{Av_4}\|\boldsymbol{Av_{min1}}\|\boldsymbol{Av_{min2}}\}$
INNER HORIZONTAL	Embedment Central	• ULS for bending: Ah_1 • ULS for axial stresses: Ah_3 • SLS for cracking: Ah_2 • Minimum geometric armor: Av_{min1} • Minimum mechanical armor: Av_{min2}	$\mathbf{max}\{\boldsymbol{Ah_1}\|\boldsymbol{Ah_2}\|\boldsymbol{Ah_{min1}}\|\boldsymbol{Ah_{min2}}\} + \boldsymbol{Ah_3/2}$
OUTER HORIZONTAL	Embedment Central	• ULS for bending: Ah_4 • ULS for axial stresses: Ah_3 • SLS for cracking: Ah_5 • Minimum geometric armor: Ah_{min1} • Minimum mechanical armor: Ah_{min2}	$\mathbf{max}\{\boldsymbol{Ah_4}\|\boldsymbol{Ah_5}\|\boldsymbol{Ah_{min1}}\|\boldsymbol{Ah_{min2}}\} + \boldsymbol{Ah_3/2}$

3.2.7 Last particularities of the software

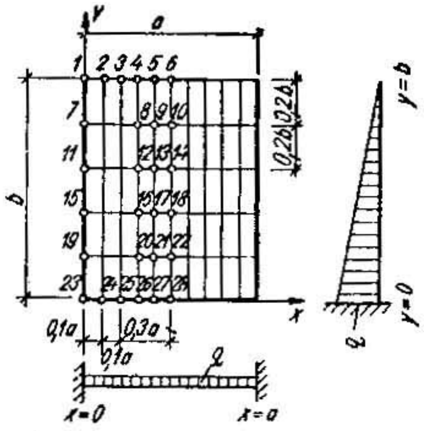
As mentioned at the beginning of the chapter, the main outputs that the program provides are: (1) total amount of steel (in Kg), (2) total amount of concrete (in m^3) and (3) total amount of lands (in m^3). The outputs are the main amount of materials required to the construction of the tank, and which will provide us the further structural and environmental analysis of the typologies studied.

From the values of the reinforcement ratios set for every section of the wall, presented in Table 3.3, we can proceed to calculate the total amount of steel required for the reinforcements in the tank. All the calculation performance is set for a lineal meter width. So once we know the amounts of armor to arrange, along with the type of bars set at the beginning of the problem, the total amount of steel required, expressed in Kg, for the construction of the designed tank in know.

Regarding the calculation of the required volume of concrete and lands, the main inputs from which we calculate their value are the dimensions of the tank designed and its typology according to its position on the field (partially buried, surface, buried).

Table 3.4 Barés Table (1970) adapted to the case of water tanks

$\gamma = \dfrac{a}{(H_w; H_s)}$	1	2	F. m
M_{x1d}	-0,0151	-0,0161	qa^2
M_{x7d}	-0,0216	-0,01502	
M_{x6d}	0,0097	0,0069	
M_{x10d}	0,0112	0,00612	
M_{y28d}	-0,0325	-0,0845	qb^2
M_{y14s}	0,007	0,0159	
M_{y18d}	0,0104	0,0107	
R_x	0,2421	0,1282	qa
R_y	0,3236	0,4584	qb



3.3 CILYNDRICAL REINFORCED CONCRETE TANKS

Figure 3.6 shows a flowchart of the structural design performance of cylindrical reinforced concrete tanks, where the steps and stages analyzed are described in the followed order.

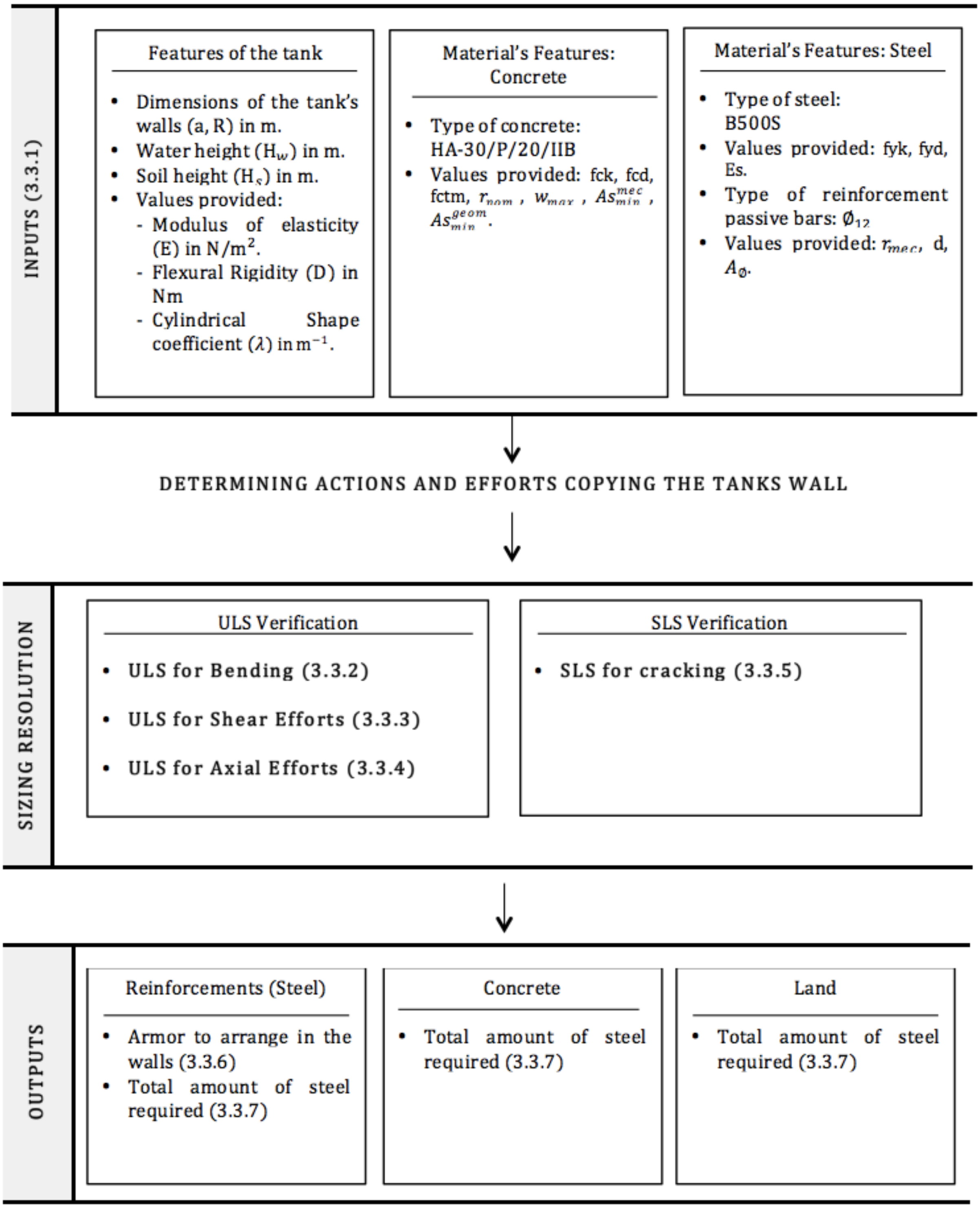


Figure 3.6 Flowchart of the structural design of Cylindrical reinforced concrete tanks

3.3.1 Preliminary Data

The first page of the program shows the preliminary data required to initiate the tanks' analysis. The inputs needed to solve the problem are mainly the height of land, which determines the deposit position relative to the ground (buried, partially buried or surface), the water height, and the radius and height of the wall as well as its thickness.

The data on the type of concrete is also listed. From this information we are able to extract the following values: fck, fcd, fctm. Being fck the characteristic compressive strength of the concrete, fcd the design compressive strength of the concrete and fctm the mean compressive strength at the age of 28 days, and which values are described in equations [3.1] and [3.2].

And from the type of environment to which the concrete is exposed, with that value and the service lifetime of the structure we know what the minimum and nominal covers that are required to fulfill the service life demands.

In turn, from the type of steel used in the reinforcements, the fyk and fyd values are known; being Es the modulus of longitudinal strain of steel with the value of $200000\,\frac{\mathrm{N}}{\mathrm{mm}^2}$, fyk the characteristic yield stress of the steel and fyd the design yield stress of the steel, which value is described by the equation [3.3].

In which γ_s is the partial safety coefficient applied in order to study the Ultimate Limit State in a persistent situation.

Setting the type of environment in which the deposit will be exposed, prior to the calculation, we set the conditions for maximum allowable crack opening and the values of minimum armor ratios, mechanical and geometric in order to avoid problems of cracking or brittle fracture. The criterion followed is explained in detail in the previous chapter, where the procedures established by the actual code are discussed.

Finally, the types of reinforcing bars that will be used in the sizing are fixed. From the bar diameter to use, the value of the mechanical reinforcement cover and effective depth of the section is fixed, both values needed to solve the problem of sizing.

With all the previous data described above, it is possible to start with the problem resolution.

The first step realized to solve the problem is the calculation of the mechanical characteristics of the tank in order to find the value of the cylindrical shape coefficient (λ), due to its cylindrical geometry, which includes the calculation of Elasticity modulus of the concrete (E) and the flexural rigidity (D), all of them values required to solve the calculation of the stresses copying the tank's walls.

The values described above are found with the following expressions,

- Modulus of Elasticity (in $\mathrm{N/m^2}$):

$$E = 8500\sqrt[3]{f_{ck} + 8} \qquad [3.21]$$

- Flexural rigidity (in Nm):

$$D = \frac{E \cdot h^3}{12(1 - v^2)} \tag{3.22}$$

In which,

v: is the Poisson coefficient, with the value of 0,2.
h: wall thickness in m.

- Cylindrical shape coefficient (in m^{-1}):

$$\lambda = \sqrt[4]{\frac{E \cdot h}{4 \cdot R^2 \cdot D}} \tag{3.23}$$

The second page of the program details the loads combination acting on the tank, mainly in function of hydrostatic pressure and earth pressure, and calculates the respective efforts to resolve all different parts that takes part into the resolution of this problem. The criteria followed to calculate each of the efforts are discussed below in each corresponding section.

3.3.2 Calculation of the wall in ultimate state for bending

3.3.2.1 Determination of the design bending moment

In order to calculate the stresses and bending moments in the wall of a cylindrical tank a linear system of four equations with four unknown factors is generated, which thanks to previous studies (Riba et al., 2006; Orbe et al., 2013) the tools to give a solution in order to simplify the problem are provided. In Figure 3.7 the direct forces in cylindrical tanks are shown, while in Figure 3.8 the efforts generated in the walls of the tank are assessed. The main assumptions made to reduce unknown factors of the system are having a small wall thickness compared to both the radius and the height of the tank and consider the wall sheet as infinitely long. The range of validity of these assumptions is for cylindrical tanks with $0 \leq D/H_w \leq 6$ (Riba et al., 2006), being D the diameter of the tank and H_w the water height.

To solve the first combination of actions, C1: 1,35x(Buoyancy), described in the section 3.4.4 from the previous chapter, we will use the formulation described as follows. The law of bending moments describes as follows:

$$M_{xd}(x) = 1{,}35 \frac{h^2 \cdot \lambda^2 \cdot \gamma_w \cdot R^2}{6(1 - v^2)} \cdot \left(-H_w \cdot e^{-\lambda x} \cdot \sin(\lambda x) + \left(H_w - \frac{1}{\lambda}\right) \cdot e^{-\lambda x} \cdot \cos(\lambda x)\right) \tag{3.24}$$

And its maximum value, which is met at the fixed section of the wall:

$$M_{xdmax} = M_{xd}(x = 0) = 1{,}35 \cdot \frac{h^2 \cdot \lambda^2 \cdot \gamma_w \cdot R^2}{6(1 - v^2)} \cdot \left(H_w - \frac{1}{\lambda}\right) \tag{3.25}$$

To solve the second combination of actions, C2: 1,5x(Soil pressure), we proceed analogously:

$$M_{xd}(x) = 1{,}5\frac{h^2 \cdot \lambda^2 \cdot \gamma_s \cdot tan^2(45 - \emptyset/2) \cdot R^2}{6(1 - v^2)} \cdot \left(H_s \cdot e^{-\lambda x} \cdot \sin(\lambda x) + \left(\frac{1}{\lambda} - H_s\right) \cdot e^{-\lambda x} \cdot \cos(\lambda x)\right) \quad [3.26]$$

And its maximum value, which is met at the fixed section of the wall:

$$M_{xdmax} = M_{xd}(x = 0) = 1{,}5\frac{h^2 \cdot \lambda^2 \cdot \gamma_s \cdot tan^2(45 - \emptyset/2) \cdot R^2}{6(1 - v^2)} \cdot \left(\frac{1}{\lambda} - H_s\right) \quad [3.27]$$

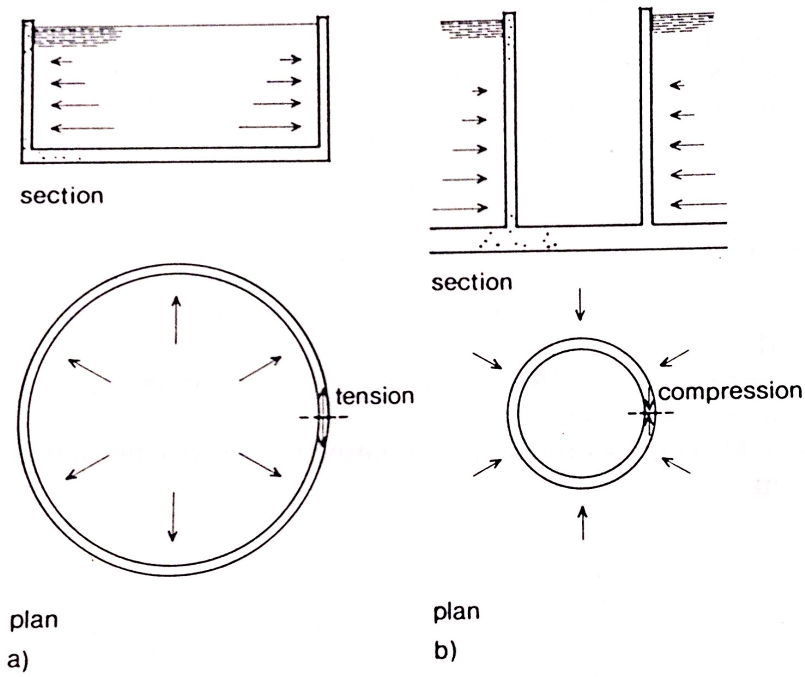


Figure 3.7 Direct forces in cylindrical tanks: a) Tensile forces, b) Compressive forces. (Anchor, 1992)

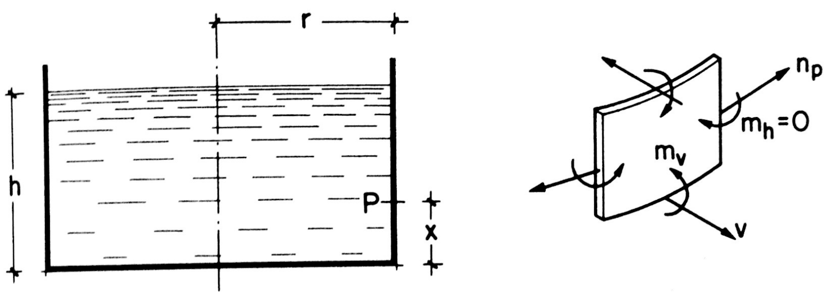


Figure 3.8 Efforts generated in the walls of a cylindrical tank. (Hormigón Armado)

Once the values of the bending moments in the different sections are known, we can assess which are the design moments of each section to size. Table 3.5 shows the nomenclature of the different reinforcement to arrange in every section of the wall.

Table 3.5 Armor nomenclature and distribution in ULS for bending

FACE OF THE WALL	SECTION	ARMOR REQUIRED (in both sections)
Inner Vertical	• Top • Bottom	Av_1
Outer Vertical	• Top • Bottom	Av_3

For the inner vertical section of the wall, we look for the envelope law of the vertical bending moments on the inner side at the junction of the combinations C1 and C2 (since both combinations can leave part of its law on the inside). With this design bending moment the required reinforcement value Av_1 will be evaluated according to the criteria established in the actual code.

In order to find the required reinforcement for bending on the outer vertical section of the wall, we look for the envelope law of the vertical bending moments on the outer side at the junction of the combinations C1 and C2 (since both combinations can leave part of its law on the outside). With this design bending moment the required reinforcement value Av_3 will be evaluated according to the criteria established in the actual code.

3.3.2.2 Calculation of the bending reinforcement

The third page of the software involves the calculation of the reinforcement required for bending stresses. To calculate the required reinforcement to deal with the bending generated in the tanks' walls, in all cases the criteria followed is the one established in the actual code EHE-08, as mentioned above. More precisely, the formulation followed to size the required reinforcement to cope with the bending stresses is the one detailed in the Annex 7 of the current code.

This methodology is aimed to obtain the required reinforcement from the design bending moment established and through the verification of the formulation set by the code. The procedure followed to calculate this amount of reinforcement is the same raised for the calculation in rectangular typology. The equations to follow in order to obtain the required result are: [3.6], [3.7], [3.8], [3.9], [3.10], [3.11], [3.12], and [3.13].

Finally, as in the rectangular typology procedure, to set the required design armor, this amount shall be compared to the minimum geometric and mechanical ratios set at the beginning of the problem, as the final amount of armor will be the higher of the three values compared; the strict amount due to calculation ($A_{s,est}$), the minimum geometrical armor ($A_{s,geom}$) and the minimum mechanical reinforcement ($A_{s,mec}$).

3.3.3 Calculation of the wall in ultimate state for shear efforts

The fourth page of the software involves the calculation of the reinforcement required due to the shear efforts generated in the walls.

In order to find the design values of the shear efforts generated in the tanks' walls, we will use the formulation described in the study developed by Riba et al. 2006. With the value of this reactions we will extract the value of the maximum shear effort generated in the tank's wall V_d.

To solve the first combination of actions, C1: 1,35x(Buoyancy), described in the section 3.4.4, the law of shear stresses describes as follows:

$$Q_{xd}(x) = 1{,}35\frac{h^2 \cdot \lambda^3 \cdot \gamma_w \cdot R^2}{6(1-v^2)} \cdot \left(H_w \cdot e^{-\lambda x} \cdot (-\cos(\lambda x) + \sin(\lambda x)) + \left(\frac{1}{\lambda} - H_w\right) \cdot e^{-\lambda x} \cdot (\cos(\lambda x) + \sin(\lambda x))\right) \quad [3.28]$$

And its maximum value, which is met at the fixed section of the wall:

$$Q_{xdmax} = Q_{xd}(x = 0) = 1{,}35 \cdot \frac{h^2 \cdot \lambda^2 \cdot \gamma_w \cdot R^2}{6(1-v^2)} \cdot \left(\frac{1}{\lambda} - 2H_w\right) \quad [3.29]$$

To solve the second combination of actions, C2: 1,5x(Soil pressure), we proceed analogously:

$$Q_{xd}(x) = 1{,}5\frac{h^2 \cdot \lambda^3 \cdot \gamma_s \cdot tan^2(45 - \emptyset/2) \cdot R^2}{6(1-v^2)} \cdot \left(H_l \cdot e^{-\lambda x} \cdot (\cos(\lambda x) - \sin(\lambda x)) + \left(\frac{1}{\lambda} - H_s\right) \cdot e^{-\lambda x} \cdot (\cos(\lambda x) + \sin(\lambda x))\right) \quad [3.30]$$

And its maximum value, which is met at the fixed section of the wall:

$$Q_{xdmax} = Q_{xd}(x = 0) = 1{,}5\frac{h^2 \cdot \lambda^3 \cdot \gamma_s \cdot tan^2(45 - \emptyset/2) \cdot R^2}{6(1-v^2)} \cdot \left(2H_s - \frac{1}{\lambda}\right) \quad [3.31]$$

As assumption in order to determine the amount of reinforcement required to cope with the shear efforts, we have taken the approach that the maximum shear effort can be absorbed by the concrete contribution V_{cu}. Thus, nor type of fence or shear reinforcement is required.

The checking procedure to validate the assumption of nor requirement of fence or shear reinforcement is comparing the value of the contribution of the concrete to the shear strength (V_{cu}) with the maximum shear effort generated in the wall (V_d). To calculate these values, the calculation procedure is the same raised for the calculation in rectangular typology. The equations to follow in order to obtain the required result are: [3.16], [3.17], [3.18] and [3.19].

3.3.4 Calculation of the wall in ultimate state for axial efforts

In the fifth page of the software the calculation of the reinforcement required due to the axial efforts generated in the walls is performed.

In this case, we have to solve the ultimate limit state for axial efforts, expressed in the combination C3: 1,00x(Buoyancy), described in section 3.4.4. The no factored load application in this action, as discussed in the previous chapter, is due to taking a steel stress value of only σ_s= 100 or 130 N/mm^2. We will proceed as follows:

$$N_{\varphi d} = 1{,}00 \cdot \gamma_w \cdot R \left[e^{-\lambda x} \cdot \left(\frac{\sin(\lambda x)}{\lambda} - H_w \cdot (\cos(\lambda x) + \sin(\lambda x)) \right) + (H_w + x) \right] \quad [3.32]$$

Following the formulation described, just at the fixed wall the value of tensile stress is zero, and its the maximum will be somewhere below the middle of the tank's wall. In this study the axial efforts, as the rest of the efforts extracted, are calculated per lineal meter, so we will get one value of the reinforcement required to cope this stresses that later, at the time of distributing the reinforcements in the tank, shall be expressed along the wall dimension. Once we have the value of the axial effort and using a steel tension of $\sigma_s = 100$ or 130 N/mm^2, we can calculate the required reinforcement as proceeds:

$$Ah_1 = \frac{N_{\varphi d}}{\sigma_s} \quad [3.33]$$

3.3.5 Wall checking under serviceability limit state for cracking

This section, treated in the sixth page of the software, describes the resolution of the serviceability limit state for cracking, and is the fifth page of the software. The problem resolution starts with the expressions according to the combinations C4: 1,00x(Buoyancy) and C5: 1,00x(Soil Pressure), described as the rest of action combinations in section 3.4.4 of the present chapter.

To solve the combination of actions C4: 1,00x(Buoyancy) will use the same horizontal and vertical bending moments that we have found from the combination C1 used in the ultimate state for bending resolution, but in this case, without applying the load increment factor, since in that case, a serviceability limit state is evaluated. Table 3.6 shows the nomenclature of the different amounts of armor to arrange in every section of the wall.

Similarly, to address the combination of actions C5: 1,00x(Land pressure) we will use the horizontal and vertical bending moments without applying the load increment factor used to solve the combination C2 from the ultimate state for bending.

For the inner vertical section of the wall, we look for the envelope law of the vertical bending moments on the inner side at the junction of the combinations C4 and C5. The reinforcement provided by the design moment for bending Av_2, must produce a maximum crack opening of $w_k \leq 0{,}2$ or 0,1 mm depending on the cracking criteria adopted.

Table 3.6 Armor nomenclature and distribution in SLS for cracking

FACE OF THE WALL	SECTION	ARMOR REQUIRED (in both sections)
Inner Vertical	• Top • Bottom	Av_2
Outer Vertical	• Top • Bottom	Av_4

In order to find the required reinforcement for the outer vertical section of the wall, we look for the envelope law of the vertical bending moments on the outer side at the junction of the combinations C4 and C5. The reinforcement provided by the design moment for bending Av_4, must produce a maximum crack opening of $w_k \leq 0{,}2$ or 0,1 mm depending on the cracking criteria adopted.

3.3.5.1 Calculation of the cracking reinforcement

The criterion for evaluating and extracting the value of the required reinforcement to address cracking in the different positions of the tank follows the criteria detailed in the actual code EHE-08. In the case of verifications relating to Cracking Limit State, the effects of actions comprise the tensions in the sections (σ_c) and the crack openings (w_k) that they cause, as applicable. Both σ_c and w_k are calculated from the design actions and the combinations described in the previous section.

As described in the last section of this chapter, in accordance with the current European Code, EHE 08, in order to avoid the appearance of compression cracks, the compressive stresses in the concrete shall satisfy the checking described in equation [3.34]. And for avoiding the cracking due to tension, the verifying criteria set by the code is the one described in equation [3.35].

In which w_k is the characteristic crack opening, calculated in accordance with the formulation presented in the section 3.4.5 in the present chapter, while $w_{máx}$ is the maximum crack opening allowable, also described in section 3.4.5 of the present chapter.

To solve this problem and find the value of the reinforcement required, the procedure is the same as described in the bending sizing section to extract the required armor to cope with the stresses generated in the walls and avoid the appearance of higher cracks than the allowable established in advanced.

In this case, as we are evaluating a serviceability limit state, the design moments selected will be the ones applied in the bending sizing problem but without applying the partial safety factor, as described in section 3.4.4. With the values of the required reinforcements known, we have to proceed verifying the two criteria set by the code in equations [3.34] and [3.35] in order to avoid the cracking due to compression and tension stresses.

3.3.6 Amount of armor to arrange in the tank's wall

The last part of the software deals with the calculation of the total amount of steel required in the tank's wall. In table 3.7, the design amount of reinforcement to arrange in every section of the wall is described.

3.2.7 Last particularities of the software

As mentioned at the beginning of the chapter, the main outputs that the program provides are: (1) total amount of steel (in Kg), (2) total amount of concrete (in m^3) and (3) total amount of lands (in m^3). The outputs are the main amount of materials required to the construction of the tank, and which will provide us the further structural and environmental analysis of the typologies studied.

From the values of the reinforcement ratios set for every section of the wall, presented in Table 3.7 we can proceed to calculate the total amount of steel required for the reinforcements in the tank. All the calculation performance is set for a lineal meter width. So once we know the amounts of armor to arrange, along with the type of bars set at the beginning of the problem, the total amount of steel required, expressed in Kg, for the construction of the designed tank in know.

Regarding the calculation of the required volume of concrete and lands, the main inputs from which we calculate their value are the dimensions of the tank designed and its typology according to its position on the field (partially buried, surface, buried)

Table 3.7 Amount of armor to arrange in the tank's walls

FACE OF THE WALL	SECTION	ARMOR REQUIRED (in both sections)	ARMOR TO ARRANGE
INNER VERTICAL	Top Bottom	• ULS for bending: Av_1 • SLS for cracking: Av_2 • Minimum geometric armor: Av_{min1} • Minimum mechanical armor: Av_{min2}	$\mathbf{max}\{\boldsymbol{Av_1}\|\boldsymbol{Av_2}\|\boldsymbol{Av_{min1}}\|\boldsymbol{Av_{min2}}\}$
OUTER VERTICAL	Top Bottom	• ULS for bending: Av_3 • SLS for cracking: Av_4 • Minimum geometric armor: Av_{min1} • Minimum mechanical armor: Av_{min2}	$\mathbf{max}\{\boldsymbol{Av_3}\|\boldsymbol{Av_4}\|\boldsymbol{Av_{min1}}\|\boldsymbol{Av_{min2}}\}$
INNER HORIZONTAL	Embedment Central	• ULS for axial stresses: Ah_1 • Minimum geometric armor: Av_{min1} • Minimum mechanical armor: Av_{min2}	$\mathbf{max}\{\boldsymbol{Ah_1/2}\|\boldsymbol{Ah_{min1}}\|\boldsymbol{Ah_{min2}}\}$
OUTER HORIZONTAL	Embedment Central	• ULS for axial stresses: Ah_1 • Minimum geometric armor: Av_{min1} • Minimum mechanical armor: Av_{min2}	$\mathbf{max}\{\boldsymbol{Ah_1/2}\|\boldsymbol{Ah_{min1}}\|\boldsymbol{Ah_{min2}}\}$

3.4 DESIGN BASIS FOR THE CALCULATION PERFORMANCE (EHE-08)

3.4.1 Introduction

Reinforced concrete tanks have been used for water, wastewater storage and treatment for decades. The engineer is asked to design a variety of square, round, and oval reinforced concrete structures that may be above, below, or partially below ground. The design of reinforced concrete tanks requires attention not only to strength requirements, but also to crack control and durability. The real challenge for the engineer is to design concrete liquid containing structures that will resist the extremes of seasonal temperature changes and a variety of loading conditions, and remain watertight.

The most important requirements related to the design of a concrete tanks include the ones that follows:

- Reduced working load stresses, and requirements for size and spacing of reinforcement
- Increased minimum reinforcement for temperature and shrinkage movement, which is dependent on the grade of reinforcing steel and the length between shrinkage dissipating joints
- Water stop requirements at all joints
- Concrete mix design requirements
- Commentary suggestions for use of shrinkage compensating concrete per EHE-08
- Properly designed, specified, and detailed structures applying the requirements of the EHE-08, along with engineering judgment and quality construction, should have a useful life of 50 to 100 years.

In the following sections the criteria established in the actual code on concrete structures, EHE-08, is described. These criteria establish the basis to follow in order to perform a sizing problem of a reinforced structure. Along with the criteria presented and the calculation procedure explain in the present chapter, the structural design of the water tanks will be performed.

3.4.2 Environmental exposure and coverings

Environmental Exposure

The type of environment must be identified before embarking on the design of the structural element, in accordance with current Code on Structural Concrete EHE (2008). The environmental exposure defines the aggressivity to which the structural element is to be subject, and it is defined by the set of physical and chemical conditions to which it is exposed.

Coverings

The concrete covering is the distance between the external surface of the reinforcement (including hoops and sitrrups) and the nearest concrete surface.

The minimum covering of a passive reinforcement is a covering depth maintained at every point on the reinforcement. According to the current code, a nominal cover value of r_{nom} shall be set out in the design and it is defined as follows:

$$r_{nom} = r_{min} + \Delta r \qquad [3.34]$$

In which r_{min} is the minimum covering and Δr the covering margin. The minimum covering is determined according to the type of environmental exposure and must be guaranteed at any point in the element, while the covering margin depends on the execution control level of the structural element. As conventional water tanks are considerate in situ elements subjected to intense execution inspection, the value set for the covering margin is 5 mm.

3.4.3 Class of concrete and reinforcement

Class of concrete

A suitable concrete quality must be ensured in order to develop a strategy based on durability. For ensuring this durability in liquid containing structures, as water tanks, specifying and supplying a concrete mix that minimizes shrinkage is critical. Concrete shrinkage depends on several factors, including cement content and aggregate. To insure that design assumptions are valid, shrinkage requirements must be specified.

Is essential to obtain a full compaction without segregation as well. In order to make this happen, the code sets quality concrete values, which are adapted to the case of water tanks and shown in the Table 3.8.

As for the type of cement, it is recommended to use those with low hydration heat. We propose the use of CEM I for reinforced concrete tanks.

Table 3.8 Values set by the Code EHE-08 adapted to the case of water tanks

Type of concrete	Maximum a/c ratio	Min cement content	Min typical resistance
Reinforced Concrete	0,5	325 kg/m^3	35 N/mm^2

Class of Reinforcement

The type of deforming bars for the passive reinforcements is:

Table 3.9 Mechanical characteristics of the Steel

Type of stell	Designation	Yield strength (N/mm^2)	Design yield strength (N/mm^2)
Weldable Steel	B500S	500	435

Due to they are the most common bars in the market.

3.4.4 Actions to be considered in the wall calculation

The main actions seeking the tanks' walls are: (1) buoyancy; (2) soil pressure and (3) thermal action, earthquake, wind, and delayed effects (shrinkage, creep and relaxation). Figure 3.9 shows the buoyancy and soil pressure coping a tank's wall.

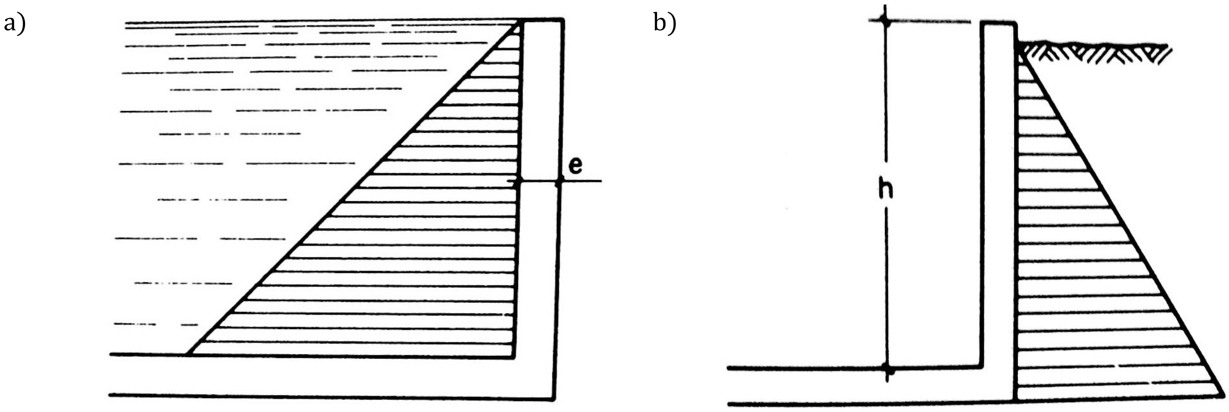


Figure 3.9 Actions seeking the tanks: a) Buoyancy; b) Soil pressure

The buoyancy $q_h(x)$ acts in the inner face of the wall and on the floor of the tank. The pressure on the wall is triangular, and will have a maximum value of:

$$q_w(x = 0) = \gamma_w \cdot H_w \qquad [3.35]$$

In which γ_w is the specific weight of the water and H_w the water height. We will the focus the study in the two worst cases, first adopting the water acting in the whole wall, whereas the second one will be considering the tank completely empty.

The Soil pressure $q_s(x)$ only acts in the outer face of the wall. The pressure on the wall is triangular as well, and will have a maximum value of:

$$q_s = \gamma_s \cdot tan^2\left(45º - \frac{\theta}{2}\right) \cdot H_s \qquad [3.36]$$

In which γ_s is the specific natural land weight; H_l represents the land height and θ the angle of internal friction.

The thermal action, earthquake, wind, and delayed effects will not be calculated, they will only be taken into consideration by adopting higher geometric quantities of the reinforcements.

According to the Code EHE, the actions' classification shall be the one that follows:

- Buoyancy: Permanent action
- Soil pressure: Permanent action of a non-constant value

Under a certain combination of the actions above, the limit states must be checked. Limit States are defined as those situations in which, when exceeded, it may be considered that the structure does not fulfill one of the functions for which it has been designed.

The Limit States that are checked for the tanks' design are the followings, according to the Code EHE Limit States classification:

- Ultimate Limit States (ULS)
- Serviceability Limit States (SLS)

Ultimate States are those that cover all Limit Stated giving rise to the failure of the structure, due to a loss in equilibrium, collapse or breakage thereof or part thereof. As for the

Serviceability Limit States, they refer to those situations in which the required functionality, comfort or aspect requirements are not fulfilled.

Every studied situation must take into account the design values of the actions, the characteristics of materials and geometric data. To determine the effect of the actions, the combined design actions according to the criteria laid down in Code EHE-08 must be considered.

The checking procedure for a certain Limit State consist in determining, first of all, the effect of the actions applied to the structure or part thereof and, second of all, the response of the structure for the limit situation being studied. The partial safety factors for actions are chosen based on the monitoring level adopted. These values correspond to a determined probability of not being exceeded during a reference period.

For every situation studied the combinations of actions shall be established, in accordance with current Code on Structural Concrete EHE (2008). For reinforced concrete tanks, the combination of actions shall be defined in accordance with the criteria established in the table that follows.

The nomenclature used in the different combinations of actions in the calculation of the reinforced tanks is first C that appeals to combination and the number assigned in after every letter follows the checking procedure in the calculation performance. All different combinations to take into account are described in Table 3.10.

Table 3.10 Actions combination for the calculation of reinforced concrete tanks

LIMIT STATE CHECKED	ACTION COMBINATION
ULS for bending and shear efforts	C1: 1,35 x q_w (Buoyancy) C2: 1,50 x q_s (Soil pressure)
ULS for axial efforts	C1: 1,00 x q_w (Buoyancy)
SLS for cracking	C4: 1,00 x q_w (Buoyancy) C5: 1,00 x q_s (Soil pressure)

As shown in the Table 3.10, the reason why the third combination of actions is not increased with a partial safety factor, even tough we are checking an ULS is because throughout the study a steel stress of only 100 or 130 N/mm^2 is adopted.

In the case of the checking of the SLS for cracking, since the determination of the crack width for elements subjected to bending and tension at the same time is not resolved satisfactorily, the following simplification shall be assumed: only cracking caused by bending is calculated, and in the end the necessary tensile armor will be added to the final amount.

3.4.5 Serviceability limit state for cracking

This limit state is extremely important because the tanks' functionality and durability relies on its proper performance. If a reinforced slab is laterally load, the concrete on the side of the tension reinforcement will extend and, depending on the loading magnitude, it will eventually crack as the load is increased. At the instant that a crack forms, it will have a positive width. Further increases in load widen the cracks that have formed and increase the stress reinforcement, as shown in Figure 3.10. For the same concrete section and load but with a greater quantity of reinforcement, the service stresses in the steel will be reduced, and the cracks widths will be narrower.

The applied load is fixed by the structural arrangement mentioned in section 3.4.4, and using the limit state design, values of slab thickness, reinforcement quantity, and reinforcement service stress must be chosen in order to ensure that the crack widths under service loads are within the appropriate values given by the class of exposure and detailed in the present section.

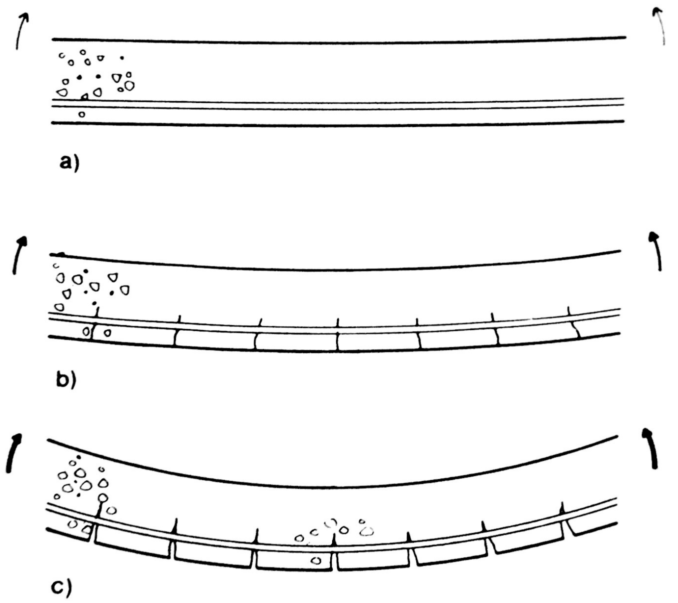


Figure 3.10 Flexural cracking: a) Concrete uncracked with low steel stresses; b) Fine cracks and increased steel stresses and c) Wide cracks and high steel stress. (Anchor, 1992)

In accordance with the current European Code, EHE 08, in order to avoid the appearance of compression cracks, the compressive stresses in the concrete shall satisfy the following:

$$\sigma_c \leq 0{,}60\ f_{ckj} \qquad [3.37]$$

In which σ_c is the compressive stress of the concrete in the verifying situation, and f_{ckj} the assumed value in the design for characteristic strength at *j* days (age of the concrete in the phase considered).

For avoiding the cracking due to tension, the verifying criteria set by the code is the one that follows:

$$w_k \leq w_{máx} \qquad [3.38]$$

In which w_k is the characteristic crack opening, while $w_{máx}$ is the maximum crack opening allowable.

Calculation of the characteristic crack opening

The characteristic crack opening shall be calculated using the following expression:

$$W_k = \beta \cdot S_m \cdot \varepsilon_{sm} \quad [3.39]$$

In which:

β: Coefficient that relates the mean crack opening to the characteristic value and is equal to 1,7, as we assume that the cracking will not be caused only by indirect actions.
S_m: Median crack spacing expressed in mm and with the following value,

$$S_m = 2c + 0{,}2s + 0{,}4k_1 \cdot \frac{\phi A_{c,eff}}{As} \quad [3.40]$$

With:
c: cover of the tensioned reinforcements, expressed in mm.
s: Distance between longitudinal bars. If $s > 15\emptyset$, s shall be taken to equal $15\emptyset$, in mm.
k_1: Coefficient representing the effect of the tension diagram in the section, with a value of 0,125.
$\emptyset$: Diameter of the thickest tensioned bar or equivalent diameter in the case of bundled bars, in mm.
$A_{c,eff}$: Area of concrete of the cover zone, in which the tension bars effectively influence the crack opening.
If $s \leq 15\emptyset$, then $A_{c,eff}$= b(unit width)· h/4
If $s > 15\emptyset$, then $A_{c,eff}$= $15\emptyset$· h/4
As: Total section of the reinforcements located in the area $A_{c,eff}$.

ε_{sm}: Mean elongation of reinforcements taking account of the collaboration of the concrete between cracks:

$$\varepsilon_{sm} = \frac{\sigma_s}{E_s}\left[1 - k_2\left(\frac{\sigma_{sr}}{\sigma_s}\right)^2\right] \geq 0{,}4 \cdot \frac{\sigma_s}{E_s} \quad [3.41]$$

With:
σ_s: Service stress of the passive reinforcement in the cracked section hypothesis, with the following value,

$$\sigma_s = \frac{M_k}{0{,}88 \cdot d \cdot A_s} \quad [3.42]$$

E_s: Modulus of longitudinal deformation of the steel.
k_2: Coefficient of value 0,5, as we will work with long-term loads.
σ_{sr} : Stress in the reinforcement in the cracked section at the moment when the concrete cracks, which is assumed to happen when the tensile stress in the most tensioned fibre in the concrete reaches the value of $f_{ctm,fl}$. Its value is the following:

$$\sigma_{sr} = \frac{b \cdot h^2}{6} \cdot \frac{f_{ctm}}{0{,}9 \cdot d \cdot As} \quad [3.43]$$

With:

Mk: Bending moment per width unit under the combination for which the cracking is verified.

d: Effective depth of the section, with value $d = h - rmec - \frac{\emptyset}{2}$
b: Unit width of the section.
h: Total depth of the section.
f_{ctm}: Mean axial tensile strength of the concrete, expressed in N/mm^2 and with the value described in [3.2]

Evaluation of the maximum allowable crack opening $w_{máx}$

The maximum allowable crack opening by the current code in the sealing cases is not completely covered. It is necessary to follow the recommendations advocated by specialists in the deposits field.

Thus for Jiménez Montoya et al (1987), when the shell of a reinforced concrete tank is subjected to alternating wet-dry or exposed to frost or aggressive agents, the maximum crack opening shall be limited to the value of 0,1 mm. In permanently buried tanks the value of 0,2 mm is admitted.

While according to the British code BS 8007 (1987), the value of 0,2 mm is admitted when the surface of the tank is exposed to very severe conditions, while in the case of critical cosmetic appearance, where efflorescence and surface oxidation are both unacceptable, a maximum crack opening of 0,1 mm is adopted.

So according to the study carried out by Riba et al., (2006), who collected the recommendations mentioned above, the following criteria arise:

Maximum allowable crack opening $w_{máx}$ in reinforced concrete tanks' walls

In the Tables 3.11 and 3.12, the criteria to establish the maximum allowable crack opening in order to develop the proper durability strategy in reinforced concrete tank's walls is described:

Table 3.11 $w_{máx}$ in the outer face of a reinforced concrete wall

OUTER FACE OF THE WALL	
Tank typology	$w_{máx}$ **(mm)**
• Buried • Partially-Buried • Superficial (protected)	0,2
• Superficial (exposed)	0,1

Table 3.12 $w_{máx}$ in the inner face of a reinforced concrete wall

INNER FACE OF THE WALL	
Tank typology	$w_{máx}$ **(mm)**
• Covered tanks thermically protected	0,2
• Unovered tanks thermically exposed	0,1

Particularities of the Serviceability Limit State for cracking in tanks

As we previously commented, the evaluation of the crack opening in surface elements simultaneously subjected to tensile and bending stresses, such as the walls and hearth of the tanks, is not satisfactorily solved. For this reason, the crack opening is determined considering only simple bending and following the criteria we have set in the previous sections above.

In accordance with the British Code BS 8007 (1987), for reinforced concrete tanks, the reinforcements due to bending forces and tensile stresses are determined independently and summed. The armor for bending is determined based on the Ultimate Limit State and the maximum allowable crack opening, while the reinforcement for tensile takes a very low value for the allowable stress of steel, which shall be the following:

- For a steel stress of $\sigma_s = 100\ N/mm^2$ we adopt the value of $w_{máx} = 0{,}1$ mm.
- For a steel stress of $\sigma_s = 130\ N/mm^2$ we adopt the value of $w_{máx} = 0{,}2$ mm.

3.4.6 Minimum armor ratios in tanks

The main objective of the need for minimum geometric ratios of reinforcement is to prevent possible cracking caused by the shrinkage of the set, temperature variations or even other actions that generally will not be covered by the tank's calculation design, and is calculated as follows:

$$A_{s_{min}^{geom}} = \boldsymbol{\rho_{min}} \cdot b \cdot h \qquad [3.44]$$

On the other hand, the minimum mechanical ratios of reinforcement shall be taken intro account in order to prevent brittle fracture of the section and simultaneously, help to control the craking. This minimum amount depends directly on the tank's geometrical configuration and its materials, and is calculated as follows:

$$A_{s_{min}^{mec}} = 0{,}04 \cdot b \cdot h\ \frac{f_{cd}}{f_{yd}} \qquad [3.45]$$

The current Code does not specify anything in reference to the minimum amount of armor in tanks, hence, basing on the recommendations set by Montoya Jiménez et al (1987), we will use the criteria that follows, always based on the total concrete section.

For the walls in rectangular reinforced concrete tanks the Table 3.12 describes the values to use, and Table 3.13 describes the values set in the case of cylindrical walls.

Table 3.13 Minimum geometric armor ratios for walls in rectangular tanks

WALLS IN RECTANGULAR REINFORCED CONCRETE TANKS			
VERTICAL ARMOR		HORIZONTAL ARMOR	
$\boldsymbol{w_{max}}$ (mm)	$\boldsymbol{\rho_{min,bending}}$	$\boldsymbol{w_{max}}$	$\boldsymbol{\rho_{min}}$
0,1	0,0020	0,1	0,0020
0,2	0,0015	0,2	0,0015

Table 3.14 Minimum geometric armor ratios for walls in cylindrical tanks

WALLS IN CYLINDRICAL REINFORCED CONCRETE TANKS			
VERTICAL ARMOR		HORIZONTAL ARMOR	
w_{max} (mm)	$\rho_{min,bending}$	w_{max}	ρ_{min}
0,1	0,0020	0,1	0,0020
0,2	0,0015	0,2	0,0015

CHAPTER 4

PARAMETRIC STUDY

4.1 INTRODUCTION

The aim of this chapter is to present the parametric study developed in this work, explaining the whole process that has been carried out and presenting the most representative results achieved. The results obtained in this study will be further used to develop the environmental assessment through the LCA methodology.

Clearly, when it comes to design a structure, many options arise to get a tank with a given volume, corresponding to various types of concrete and shapes. Mainly, the rectangular and cylindrical reinforced concrete tanks will be discussed in this study. We have decided to study the widest possible tanks population and go delimiting the parameters that determine the structural behavior in the sizing phase, in order to provide the structural design which best optimize the materials required.

It is important to note that from a structural point of view, all cases analyzed that meet the criteria established by the code are considered structurally optimal. When it comes to optimizing, from the structural point of view in this work, it is understood to meeting the best structural design, which minimizes the materials required in its construction. That translates in finding the configuration that requires the less materials consumption for a volume given in advance.

4.2 GOALS AND SCOPE

The main goal of the structural analysis of the reinforced tanks is to obtain the larger variety of design possibilities in order to perform the design of a given volume with the most optimal dimensions of it. The specific goals of the study are:

- To select a large variety of representative cases of rectangular cylindrical water tanks comprising realistic ranges of volumes, dimensions, wall thicknesses and positions.
- To determine which the optimal wall thickness is for each volume defining a curve where the materials consumptions are shown.
- To determine which configuration requires the less material consumption for a given volume in both typologies, rectangular and cylindrical.
- To study in depth the cylindrical cases depending on the variables involved in the parametric study in order to provide conclusions that must agree with the further environmental assessment following the LCA methodology.

4.2.1 Methodology applied in the parametric study

The structural design and study of all the case studies presented has been performed through the calculation program detailed in Chapter 3. As mentioned, after processing all the preliminary data and performing the checks related to the limit states, the required amount of armor to deal with the stresses generated in the tanks wall and to ensure the proper functioning of it are know. The outputs that the software generates are the required values to process and develop the further environmental analysis of the impacts generated in the construction and design of the tank, which are: amount of concrete (in m^3), amount of steel (in Kg) and land volume (in m^3).

Although in this parametric study, the outputs treated and analyzed have been the amount of reinforcement required to deal with the stresses generated in the tanks, expressed in total amount of armor (in cm^2) and total amount of steel required (in Kg) and the amount of concrete (in m^3). With these values it is possible to perform the design of a given volume, which requires the less materials consumption.

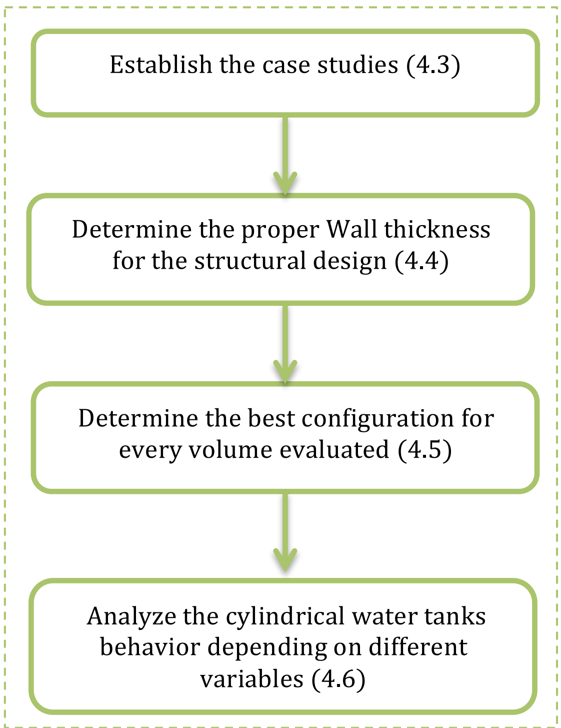


Figure 4.1 Flowchart of the parametric study

4.3 CASE STUDIES

The characteristics and features considered for the structural optimization of water tanks are the dimensions (diameter, dimensions of the wall and height), its position on the ground (superficial, partially-buried and buried), the wall thickness (from 0,15 m to 0,1·Hw considered in each height case evaluated, considering new thicknesses every 5 cm), the amount of armor (the minimal geometric ρ_{geom}, minimal mechanic ρ_{mec}, and the strict due to calculation ρ_{est}) and capacity (volume for water storage).

In advance, for every volume evaluated there are 504 different cases depending on the dimensions, the position, the wall thickness and the amount of armor considered.

Regarding the capacity of the water tank, the following 7 volumes were considered (in m^3): 100, 500, 1,000, 2,500, 5,000, 7,500 and 10,000. These volumes cover the range of water tanks that are more prone to be found in small to medium municipalities.

This means that for each geometrical configuration evaluated and studied there have been 3528 different cases corresponding to the cylindrical and rectangular tanks. In total, 7056 different cases have been analyzed. The specific dimensions for all the cases can be found at Table 4.1.

4.3.1 Rectangular reinforced concrete case studies

All rectangular tanks that have been studied in the sample are raised with two cells. This is a good recommended practice in order to continue providing service in the event of having to repair or clean one of the cells. We have attempted to search a geometry as square as possible in the dimensions established in all cases.

The dimensions of rectangular water tanks depend on its height and walls dimension. For each of the 7 different volumes, 7 different configurations were considered. For all the volumes, the same heights were defines, although the walls dimensions are different depending on the case. The heights considered are (in m): 2.5, 3.5, 4.5, 5.5, 6.5, 7.5 and 8.5. Nevertheless, the specific dimensions for all the cases can be found at Table 4.1.

4.3.2 Cylindrical reinforced concrete case studies

The cylindrical tanks evaluated have not been divided into two cells as was the rectangular cases, as it is a very unusual practice in the cylindrical typology.

The dimensions of cylindrical water tanks depend on its height and radius. For each of the volumes, 7 different options were considered. For all the volumes, the same heights were defined, although the diameters are different depending on the case The heights considered are (in m): 2.5, 3.5, 4.5, 5.5, 6.5, 7.5 and 8.5. Nevertheless, the specific dimensions for all the cases can be found at Table 4.2.

4.4 WALL THICKNESS

Regarding to the parameters involved in the sizing process of the structural design, one of the most influential on the behavior of the tanks with the loads applied is the thickness of the wall. Not only helps in analyzing the evolution of the stresses generated, is also responsible for ensuring that the values of the shear efforts generated are lower than the contribution of the concrete, and thus, avoid the requirement of fence or shear reinforcement. Finally, a proper value of the wall thickness must be chosen in order to ensure that the crack widths under service loads are within the appropriate values given as the maximum allowable crack opening in the slabs of the wall (Anchor, 1992).

The minimum recommended wall thickness for structural and constructional reasons is 30 cm (CEDEX, 2010). The overall thickness of a wall should be no greater than necessary, as extra thickness will cause higher thermal stresses when the concrete is hardening.

Even though, as mentioned above, to study the structural behavior of the walls we have analyzed, a large range of thickness to find which of them provides the best design were established. The aim of this section is to study the materials consumption variation depending on the different wall thicknesses fixed for every dimensional case analyzed for both typologies. This is done in order to conclude that as many previous studies recommended (AWWA, 1995; Walski, 2000; CEDEX, 2010; Riba et al., 2006), to establish a wall thickness of 30 cm results the best option, not only from a constructive point of view, but also from an optimal structural one.

In the Figures 4.2 and 4.3 through graphics, for each volume evaluated, the evolving reinforcement ratio (the one chosen for sizing) depending on the different wall thicknesses is shown, corresponding to the partially buried configuration is presented, as the results don't present much variation depending on the configuration evaluated. Nevertheless, the absolute results appear in Appendix B.

Even though the apparent monotony of the reinforcement ratios variation with the different thicknesses, we conclude that in most cases the most appropriate wall thicknesses to take it as the standard thickness for the deposits design is 30 cm.

4.5 OPTIMAL GEOMETRICAL CONFIGURATION FOR A GIVEN VOLUME

Based in the materials amount results with the wall thickness variable set (30 cm) we will evaluate the best design configuration that provides the less material consumption for each typology studied. In Table 4.3, the results from the best geometrical configuration for both typologies are shown. Nevertheless, the results from all the cases evaluated appear in Appendix B.

Table 4.3 Best geometrical configurations for Rectangular and Cylindrical tanks with a given volume

	Rectangular tanks			Cylindrical tanks		
Volumes (in m³)	Partially Buried	Surface	Buried	Partially Buried	Surface	Buried
100	C_2 (a=3,00; b_1=5,50; b_2= 3,00)			C7 (a=8,00; R=2,00)		
500	C_1 (a=2,00; b_1=15,00; b_2= 8,50)			C7 (a=8,00; R=4,50)		
1000	C_3 (a=4,00; b_1=14,00; b_2= 9,00)			C7 (a=8,00; R=6,50)		
2500	C_2 (a=3,00; b_1=18,00; b_2= 55,00)			C7 (a=8,00; R=2,00)		
5000	C_2 (a=3,00; b_1=42,00; b_2= 20,00)			C7 (a=8,00; R=2,00)		
7500	C_3 (a=4,00; b_1=47,00; b_2= 20,00)			C7 (a=8,00; R=2,00)		
10000	C_3 (a=4,00; b_1=51,00; b_2= 25,00)			C7 (a=8,00; R=2,00)		

Regarding the best geometrical configuration in the rectangular typology, as can see there is no monotony in the results shown, each volume evaluated has associated a particular configuration that requires the less material consumption.

On the other hand, in the cylindrical typology, it is shown that the lower requirements of concrete and reinforcing steel for the construction of cylindrical water tanks are the configurations that present larger heights (and hence shorter diameters) for all volumes evaluated.

Table 4.1 Rectangular water tanks case studies

RECTANGULAR WATER TANKS (Partially Buried, Surface, Buried)																					
Heights	Case 1 (H = 2,5)			Case 2 (H = 3,5)			Case 3 (H=4,5)			Case 4 (H = 5,5)			Case 5 (H = 6,5)			Case 6 (H = 7,5)			Case 7 (H = 8,5)		
Wall thickness	[0,15 : 0,05 : 0,3]			[0,15 : 0,05 : 0,3]			[0,15 : 0,05 : 0,4]			[0,15 : 0,05 : 0,5]			[0,15 : 0,05 : 0,6]			[0,15 : 0,05 : 0,7]			[0,15 : 0,05 : 0,8]		
Armor ratios	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}
Dimensions	a	b_1	b_2	a	b_1	b_2	a	b_1	b_2	a	b_1	b_2	a	b_1	b_2	a	b_1	b_2	a	b_1	b_2
100 m^3	2	7,5	3,5	3	5,5	3	4	5	2,5	5	4	2,5	6	4,5	2	7	4	2	8	3,5	2
500 m^3	2	15	8,5	3	17	5	4	12,5	5	5	10	5	6	9,5	4,5	7	9	4	8	8	4
1000 m^3	2	25,5	10	3	19	9	4	14	9	5	20	5	6	17	5	7	14,5	5	8	12,5	5
2500 m^3	2	42	15	3	28	15	4	32	10	5	26	10	6	21	10	7	18	10	8	16	10
5000 m^3	2	51	25	3	42	20	4	42	15	5	34	15	6	28	15	7	24	15	8	32	10
7500 m^3	2	63	30	3	51	25	4	38	20	5	42	15	6	36	15	7	36	15	8	32	15
10000 m^3	2	72	35	3	56	30	4	51	25	5	51	20	6	42	20	7	36	20	8	32	20

Table 4.2 Cylindrical water tanks case studies

CYLINDRICAL WATER TANKS (Partially Buried, Surface, Buried)																					
Heights	Case 1 (H = 2,5)			Case 2 (H = 3,5)			Case 3 (H=4,5)			Case 4 (H = 5,5)			Case 5 (H = 6,5)			Case 6 (H = 7,5)			Case 7 (H = 8,5)		
Wall thickness	[0,15 : 0,05 : 0,3]			[0,15 : 0,05 : 0,3]			[0,15 : 0,05 : 0,4]			[0,15 : 0,05 : 0,5]			[0,15 : 0,05 : 0,6]			[0,15 : 0,05 : 0,7]			[0,15 : 0,05 : 0,8]		
Armor ratios	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}	ρ_{strict}	ρ_{geom}	ρ_{mec}
Dimensions	a	R		a	R		a	R		a	R		a	R		a	R		a	R	
100 m^3	2	4		3	3,3		4	3		5	2,6		6	2,4		7	2,2		8	2	
500 m^3	2	9		3	7,5		4	6,5		5	5,7		6	5,2		7	4,8		8	4,5	
1000 m^3	2	13		3	10,5		4	9		5	8		6	7,5		7	7		8	6,5	
2500 m^3	2	20		3	16,5		4	14,5		5	13		6	12		7	11		8	10	
5000 m^3	2	28,5		3	23,5		4	20		5	18		6	16,5		7	15,5		8	14,5	
7500 m^3	2	35		3	28,5		4	24,5		5	22		6	20		7	18,5		8	17,5	
10000 m^3	2	40		3	33		4	28,5		5	25,5		6	23,5		7	21,5		8	20	

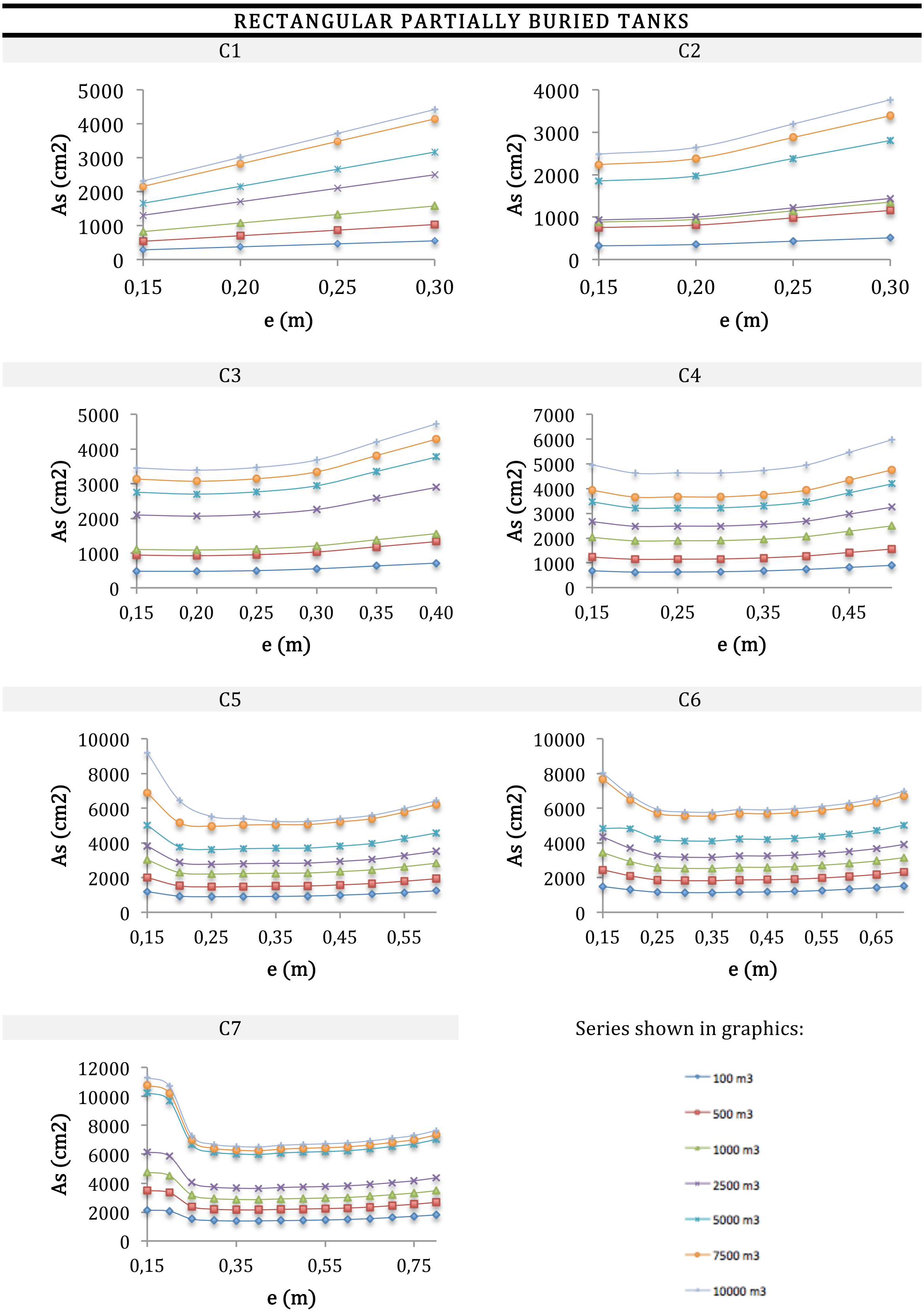


Figure 4.2 A_s f(e) Reinforcement ratio variation depending on the wall thicknesses evaluated for each volume in Rectangular partially buried tanks

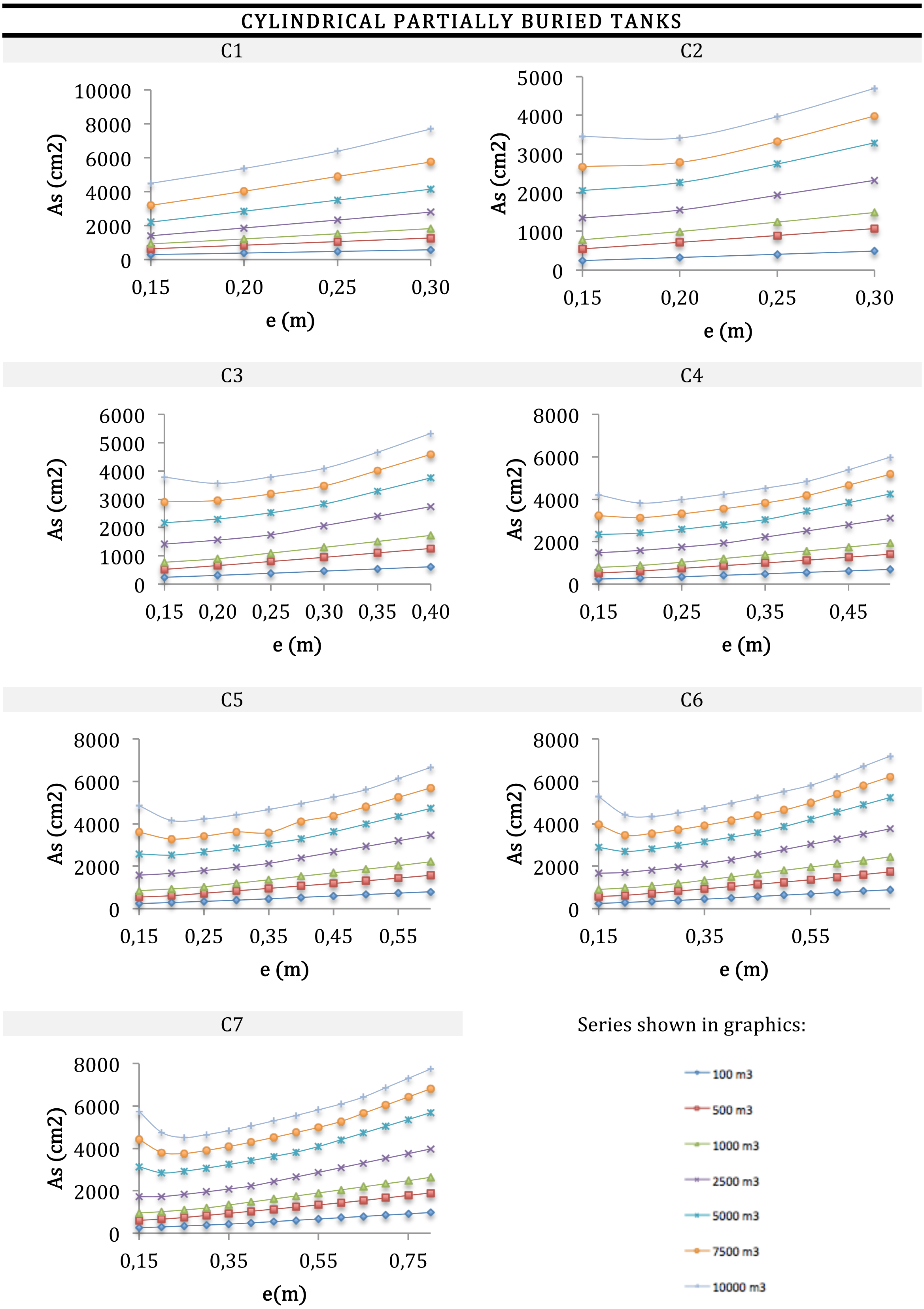


Figure 4.3 A_s f(e) Reinforcement ratio variation depending on the wall thicknesses Cylindrical tanks

4.5.1 Rectangular vs Cylindrical tanks for a given volume

The aim of this section is to evaluate the materials consumption for each case given as the optimal one for every volume evaluated in section 4.5 in both typologies, rectangular and cylindrical. Comparing the results, we want to conclude which typology configuration provides the best optimization of materials with a given volume.

The evolving materials consumption expressed by the ratio $\frac{\text{Kg Concrete}}{\text{Kg Steel}}$ with the range of volumes evaluated in both typologies, rectangular and cylindrical, is shown in Figure 4.4.

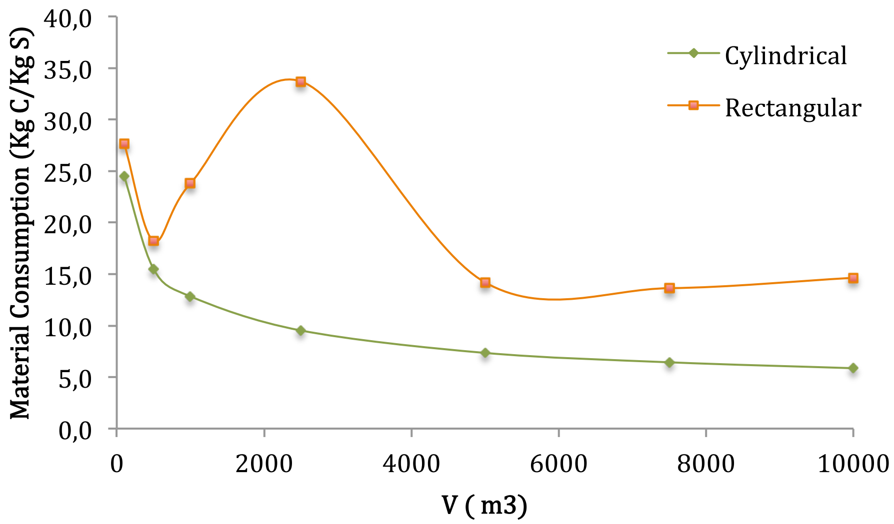


Figure 4.4 Evolve of the materials consumption with volumes for Cylindrical and Rectangular tanks

As shown in Figure 4.4, the cylindrical configuration of the tanks provides a better optimization of the materials required for its construction. This graphics confirms that the cylindrical geometry allows a greater optimization of the materials used by getting the minimum perimeter (which translates in a lower concrete consumption) with a given height and volume (CEDEX, 2010).

Also, this materials optimization gets better as the capacity of the tank increases, the relationship with the materials consumption and the volume evaluated shows that for bigger volumes, the perimeter of the tank is better optimized. It must be highlighted the difference notice in rectangular tanks of 1000 and 2500 m^3. This shows that the perimeter for these given volume is not optimize with the configuration set, requires bigger concrete consumption in relation with the reinforcements.

Based on that, from now own, the structural analysis that follows and the further environmental assessment will be focus in cylindrical water tanks, for being the configuration that provides greater optimization of materials.

4.6 CYLINDRICAL REINFORCED CONCRETE TANKS ANALYSIS

In the overall study, which includes the environmental assessment of the results obtained in this structural analysis, and is described in the next chapter; only the cylindrical tanks have been treated. The best configuration in order to obtain an optimal tank is the one that for a given height and volume, gets the minimum perimeter, which translates in an optimization of the materials.

Through a cylindrical geometry configuration, a greater optimization of the materials used is allowed, as it gets the minimum perimeter with a given height and volume.

4.6.1 Depending on volume

In section 4.5, for each volume given and for each typology according to its position on the ground (partially buried, surface and buried) the optimal geometrical configuration has been chosen. In the case of cylindrical tanks, for all volumes, the most optimal dimension from the point of view of materials requirement is the tallest, Case 7 within 7 evaluated cases of different heights (2-8 m).

In the graphics presented in Figure 4.5, the evolution of the required reinforcement depending on the volume evaluated is shown. Each function represent different reinforcement ratios, which are classified as follows: (1) strict amount of reinforcement to cope with the efforts generated in the tanks (ρ_{strict}), (2) minimum geometrical reinforcement ratio (ρ_{geom}) and (3) minimum mechanical reinforcement ratio (ρ_{mec}). The aim of this analysis is to see how and when an amount prevails to another for each tank configuration analysed (partially buried, surface and buried).

As reflected in Figure 4.5, the monotony as to how the amount of steel evolves and as when an amount prevails to another in order to design the structure is appreciable. In most of the cases studied, the strict reinforcement ratio (ρ_{strict}) adopts the same value as the minimum geometrical reinforcement (ρ_{geom}). The reason for that is because the efforts generated in the walls are not reliable when it comes to solve the problem of sizing, in most cases prevails the SLS for cracking criteria. In order to met with the criteria set by the actual code (EHE-08), a minimum amount of reinforcement is required, which is defined by the previous establishment of the maximum allowable crack openings. Hence, no difference is seen.

Nevertheless, in the buried position typology, as this configuration must deal with the tension produced by the buoyancy and the compression resulted from the soil pressure, the efforts that shall be coped by the walls are higher as the tanks capacity increases. That fact translates to a prevalence of the strict amount of reinforcement to cope with the efforts generated in the tanks (ρ_{strict}) above the minimum ratios as the volume studied increases.

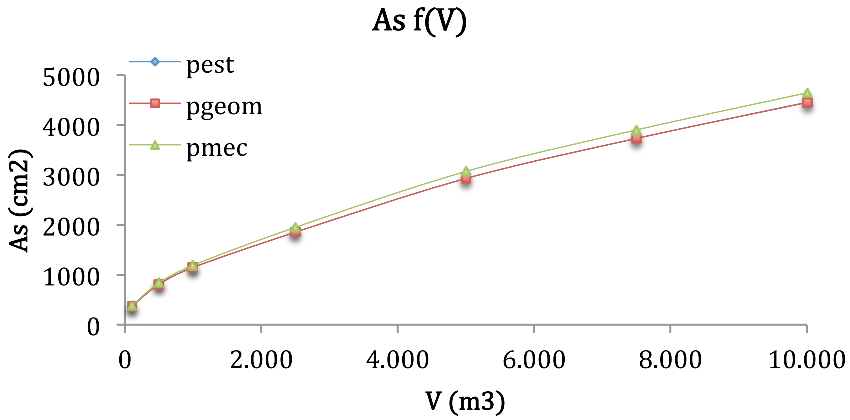
In the first instance, we can confirm that the tank configuration which requires the higher materials consumption is the buried one (Figure 4.5c), being the partially buried typologies the most optimal choice in order to consume the less amount of materials. Nonetheless, this assumption will be confirmed in section 4.6.2 and with the further environmental analysis, taking into account different parameters, an overall conclusion will be assessed.

4.6.2 Optimal position of the tank

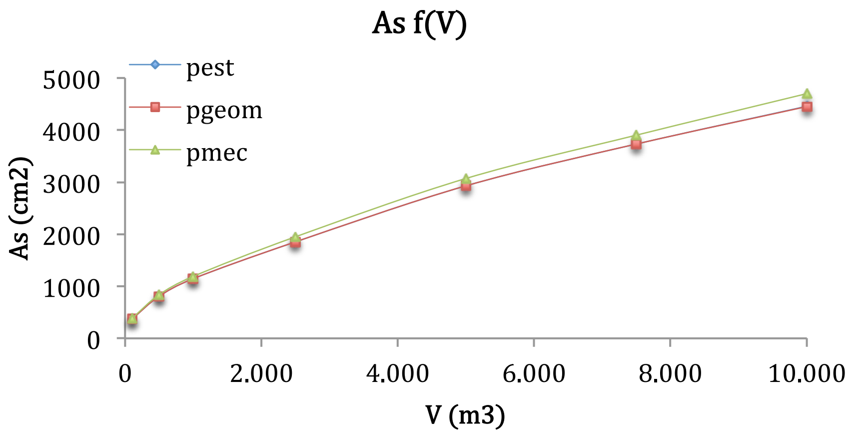
In Figure 4.6, for each cylindrical tank typology (partially buried, surface or buried), the evolving of the materials consumption with the optimal geometrical configuration chosen for each volume is shown. The chosen variables have been expressed by the following ratios: (1) the materials consumption is expressed in terms of $\frac{\text{Kg Steel}}{\text{Kg Concrete}}$ and (2) the geometrical configuration is shown as $\frac{\mathrm{D}}{\mathrm{H}_w}$.

Based on what is shown in Figure 4.6, we can confirm that the tank configuration that requires the higher materials consumption is the buried one. And the optimal choice in terms of less material consumption is the partially buried typology, even though it is appreciated as it enhances the volume of the tanks evaluated.

a) Partially Buried



b) Surface



c) Buried

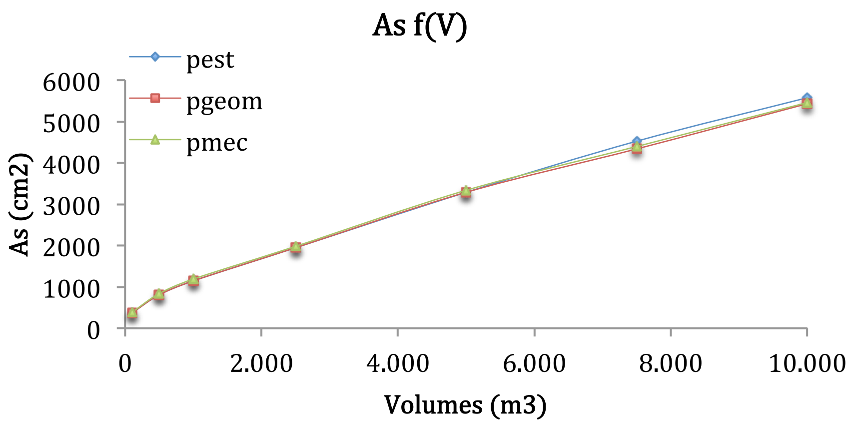


Figure 4.5 A_s variation depending on volumes: a) Partially buried; b) Surface; c) Buried

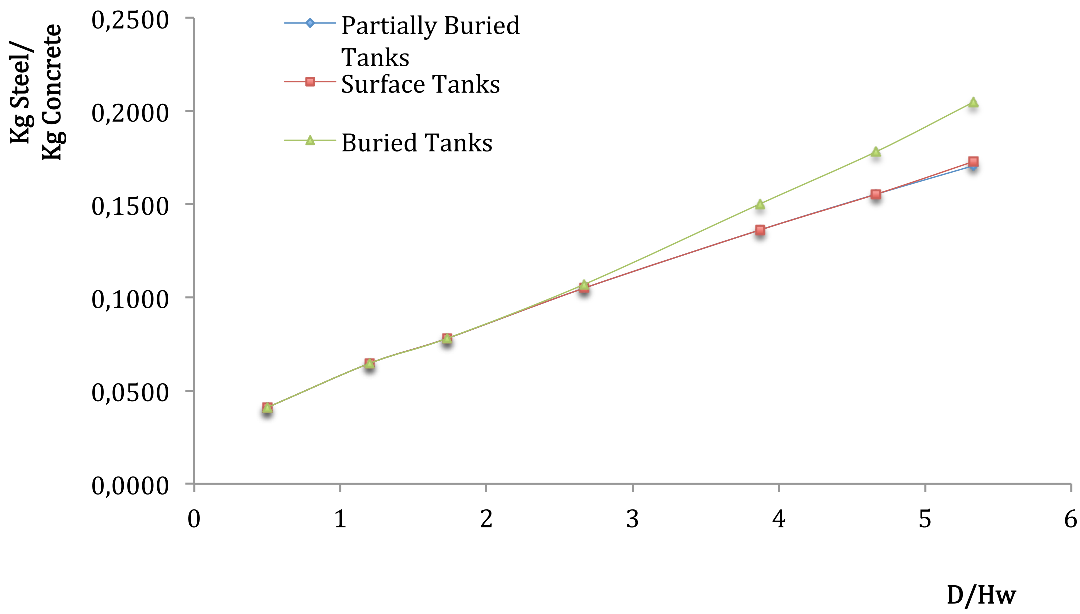


Figure 4.6 Material consumption depending on the geometrical configuration, for the different typologies according to the different positions of the tank

4.6.3 Depending on height for the 2500 m³ case study

As shown in next chapter through an environmental assessment, the most optimal configuration from all the cases studies is the volume of 2500 m^3. In Figure 4.7, the evolution of the required reinforcement depending on the heights from the different geometrical configurations evaluated for each tank typology (partially buried, surface and buried) is shown. Each function represents different reinforcement ratios, which are classified as in Figure 4.5. The aim of this analysis is to confirm that the most optimal dimension from the point of view of materials requirement is the tallest, Case 7 within 7 evaluated cases of different heights (2-8 m). This time, the wall thickness is fixed (30 cm) and it is deeply analyzed for the most representative case.

In accordance with what is shown in Figure 4.6, we can confirm that the tank configuration that requires the less materials consumption is the tallest for each typology evaluated, as the materials consumption decreases while we set higher walls in the configurations.

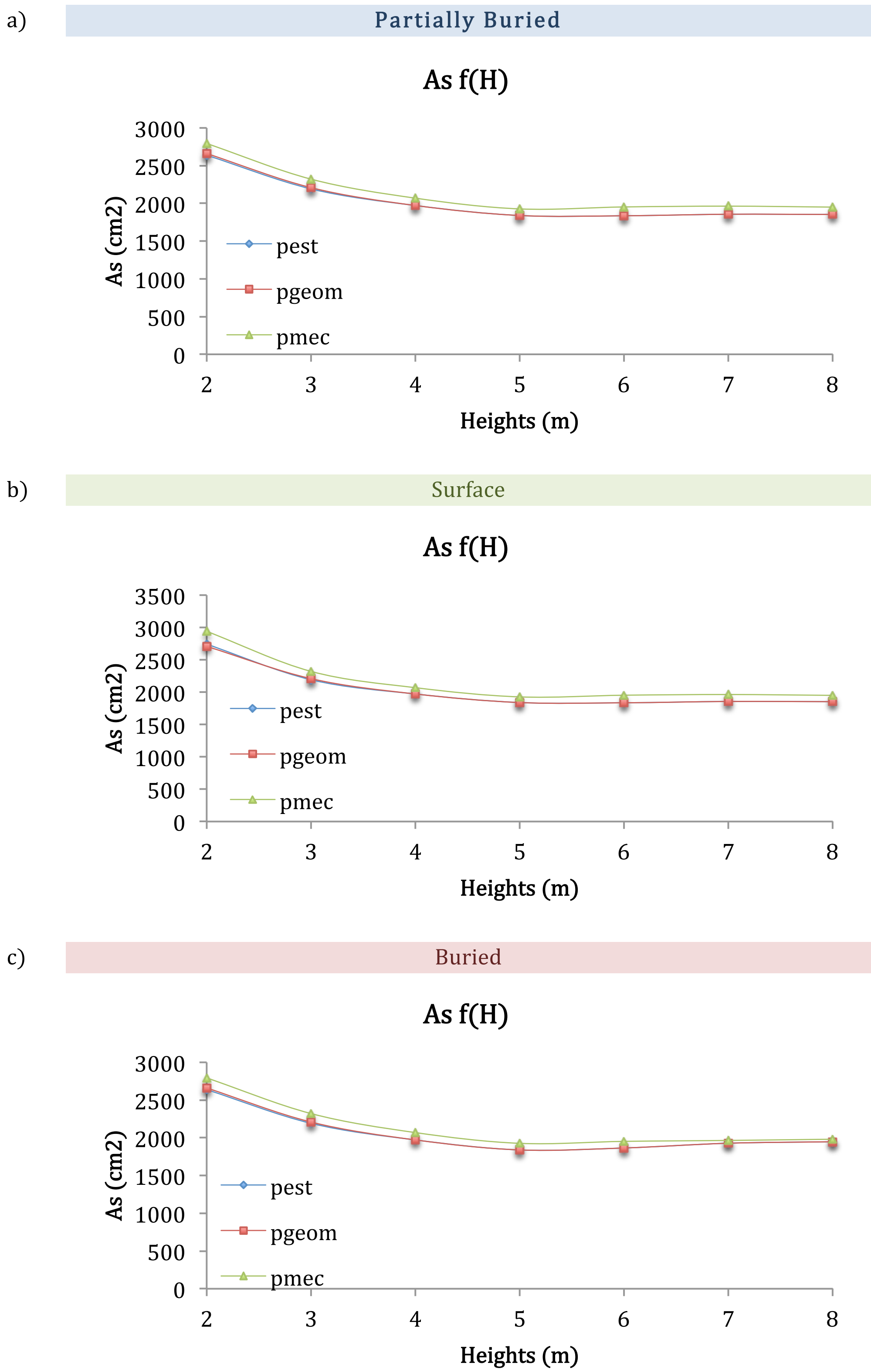


Figure 4.7 A_s variation depending on tank heights: a) Partially buried; b) Surface; c) Buried

CHAPTER 5

ENVIRONMENTAL ANALYSIS

5.1 INTRODUCTION

Along with the collaboration of the Institute of environmental sciences and technology (ICTA) from the UAB, we have conducted a study consisting of an initial structural analysis together with the further environmental study of the structural results.

In the framework of the urban water cycle (UWC), this study consists in an environmental assessment of the drinking water and distribution network (DWTDN) in response to the need for optimization detected in a previous study (Sanjuan-Delmás et al. 2014).

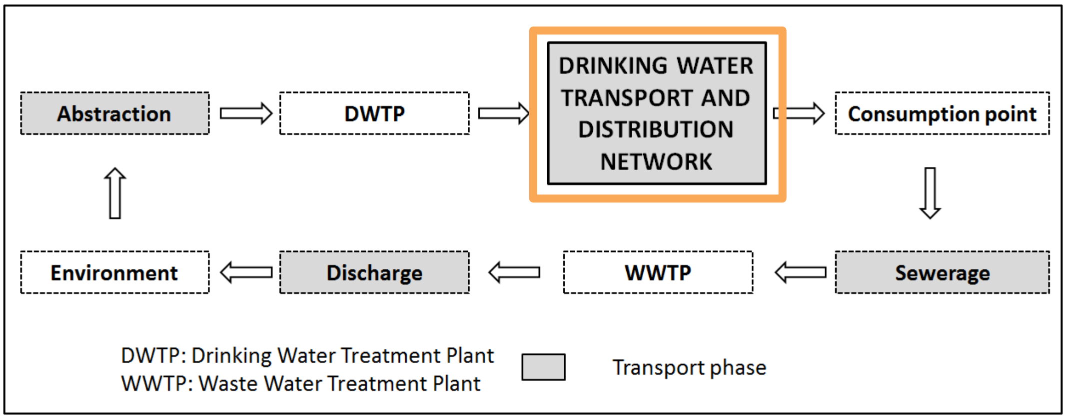


Figure 5.1 Stages of the urban water cycle and system under study

The system under study in the present analysis is the drinking water transport and distribution network (DWTDN), an infrastructure which can account for between the 20 an 40% of the environmental impacts in the UWC (Amores et al. 2013; Lemos et al. 2013). Within the DWTDN composition, three phases differ: construction, use and maintenance. The impacts generated by each phase have been previously studied. In the construction phase, most of the impacts occur during the expansion of the network (Venkatesh and Brattebø 2011), while regarding the use phase the energy consumption for pumping the water is what generates most of the impacts (Piratla et al. 2012). Finally, mention that the environmental impacts due to the maintenance phase are negligible in contrast with the previous phases (Del Borghi et al. 2013; Piratla et al. 2012; Venkatesh and Brattebø 2011).

The present chapter presents the performance of the environmental study. First, a section where the goal and scope of the study are detailed followed by the methodology applied along with the chosen cases analyzed. Finally, the results of the study are presented. To study the environmental impacts of the water tanks, the cases that will be the subject of the study appear in *Appendix B.*

5.2 GOAL AND SCOPE

Whereas several guidelines focused on the DWTDN technical aspects are published (EPA, 2002; AWWA, 1995; Walski, 2000; CEDEX, 2010), there is a lack of research regarding its environmental impact and sustainability. This study aims to provide data about the environmental impacts of structurally optimised water tanks as well as information about which options regarding its design are environmentally preferable.

5.2.1 Objectives

The main goal is to optimise cylindrical water tanks from a structural and environmental perspective. This optimization will be done through quantifying the environmental impacts and determining the most environmental friendly structural design. The specific goals of the study are:

- To compose an inventory of the material and energy inputs in the life cycle of a DWTDN.
- To analyse the environmental impacts of the structurally optimised cylindrical tanks following the LCA methodology.
- To determine which the optimal water tank is for each volume and define a curve for the calculation of the environmental impacts of the optimal cases.

5.2.2 Functional unit

The functional unit (FU) is the capacity of storing one cubic meter of water including the production, transport, installation and end of life of the water storage tank. Thus, the resulting total impact of the tank has been divided by its total capacity for each of the impact categories (impact /m^3 of water stored).

5.2.3 Materials and methods

Figure 1 shows the life cycle stages of the system under assessment along with the system boundaries and the different elements considered for each of the stages. As the present study focuses on the construction phase evaluation, the operation phase has been excluded due to the large variety depending on the case studied.

5.2.4 Environmental calculation tools

The environmental impacts of the DWTDN are calculated applying the life cycle assessment (LCA) (ISO 14040, 2006). The software Simapro 7.3 was used, along with the calculation method CML 2001 V2.05.

According to the environmental product declaration of construction products (EN 15804, 2011), the impact categories selected were Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Layer Depletion (OLDP), Photochemical Oxidation (PCOP) and Cumulative Energy Demand (CED).

All the environmental information has been taken from Ecoinvent 2.2 database (ecoinvent, 2009), linked to the Simapro 7.3 software. The data related to the amount of energy and materials consumed in the processes for the construction of water tanks ware retrieved from the Institute of Technology of Catalonia (Metabase Itec, 2010).

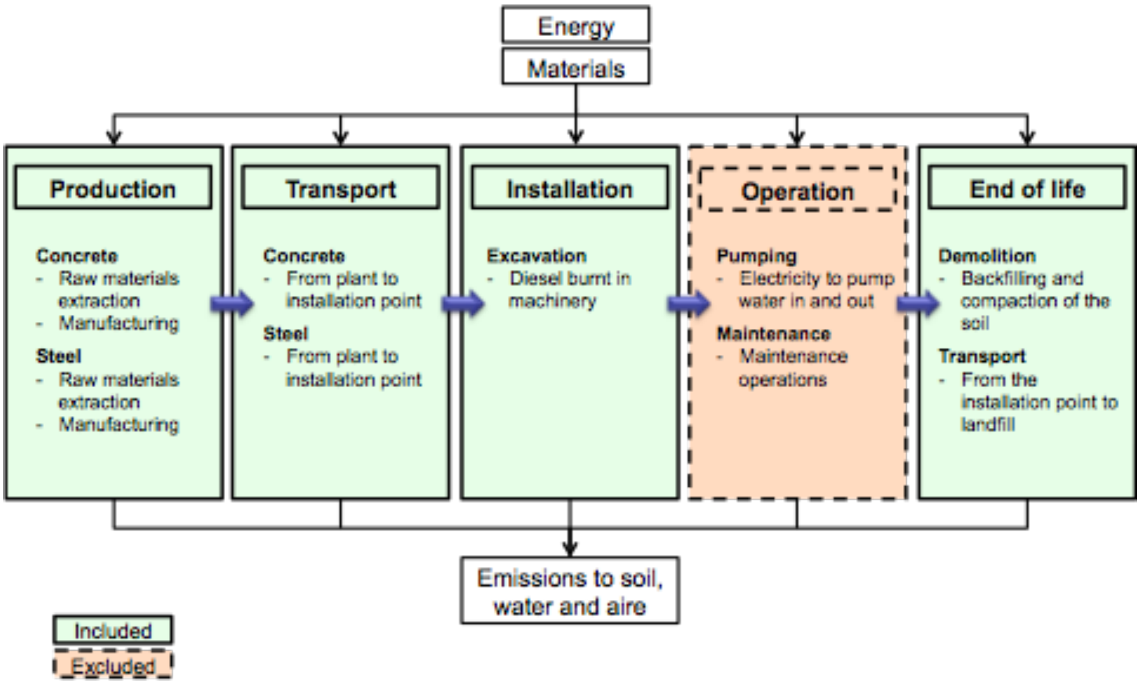


Figure 5.2 Life-cycle diagram and system boundaries of water tank.

5.3 CASE STUDIES

The characteristics considered for the optimization of cylindrical water tanks are the dimensions (diameter and height), position (superficial, partially-buried and buried) and capacity (volume for water storage). In total, 147 different cases have been analysed.

Regarding the capacity of the water tank, the following 7 volumes were considered (in m^3): 100, 500, 1,000, 2,500, 5,000, 7,500 and 10,000. The dimensions of cylindrical water tanks depend on its height and radius. For each of the volumes, 7 different geometrical configurations were considered with same heights but with different radius depending on the case. The heights considered are (in m): 2.5, 3.5, 4.5, 5.5, 6.5, 7.5 and 8.5, always provided with a coating of 50 cm. Table 5.1 shows all the specific dimensions for all the cases under assessment.

Three different positions were considered: buried, partially buried and superficial. The nomenclature has been done including the following aspects of the tank:

- Cylindrical typology (C)
- Position: superficial (S), buried (B), partially-buried (P)
- Volume: capacity in cubic meters [100 – 10000]
- Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m)

Therefore, the code "CB5006" would state for a buried cylindrical tank with 500 m^3 capacity and 6.5 m in height.

Table 5.1 Specific dimensions of all the case studies

Heights (m)	Volumes (m^3) and Radius (m)						
	100	500	1000	2500	5000	7500	10000
2,50	4,00	9,00	13,00	20,00	28,50	35,00	40,00
3,50	3,30	7,50	10,50	16,50	23,50	28,50	33,00
4,50	3,00	6,50	9,00	14,50	20,00	24,50	28,50
5,50	2,60	5,70	8,00	13,00	18,00	22,00	25,50
6,50	2,40	5,20	7,50	12,00	16,50	20,00	23,50
7,50	2,20	4,80	7,00	11,00	15,50	18,50	21,50
8,50	2,00	4,50	6,50	10,00	14,50	17,50	20,00

5.4 MAIN RESULTS AND DISCUSSIONS

5.4.1 Optimization of the dimension

Table 5.2 shows the comparison of the environmental impacts for the largest and the smallest partially buried water tanks. These results are shown in order to represent the results regarding the different heights and diameters assessed for cylindrical water tanks.

As shown in Table 5.2, higher water tanks hold significantly lower environmental impacts, having the highest tanks around half the impact of the lowest for 100 m^3 water tanks and around one third for 10000 m^3 tanks in all the impact categories analysed. These differences in the environmental impacts is due to the lower requirements of concrete and reinforcing steel, as larger heights and hence shorter diameters configurations, gets the minimum perimeter for a given volume.

5.4.2 Optimization of the position

This section aims to find which position of tank (buried, partially buried and surface) holds the lowest amount of environmental impacts. The analysis was made through comparing the impacts generation in the different positions in all volumes studied.

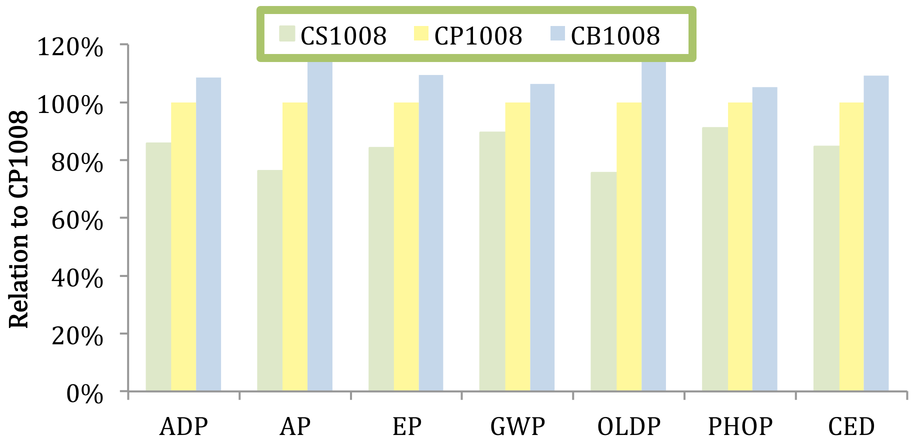
To narrow the case studies, the comparison was made for the optimal dimension according what have been found in section 5.4.1 (8,5 m in height).

Table 5.2 Comparison of the environmental impacts of 100 and 10,000 m^3 water tanks considering 7 different dimensions

	Percentage of environmental impact*						
	CP1002	CP1003	CP1004	CP1005	CP1006	CP1007	CP1008
ADP	100%	74%	66%	55%	51%	50%	45%
AP	100%	79%	74%	63%	61%	62%	55%
EP	100%	74%	66%	54%	51%	49%	44%
GWP	100%	78%	73%	63%	61%	63%	56%
OLDP	100%	80%	76%	66%	64%	66%	59%
PHOP	100%	72%	62%	50%	45%	43%	38%
CED	100%	75%	68%	57%	54%	53%	48%
	CP100002	CP100003	CP100004	CP100005	CP100006	CP100007	CP100008
ADP	100%	55%	42%	38%	36%	33%	31%
AP	100%	59%	48%	44%	42%	38%	36%
EP	100%	54%	42%	38%	36%	33%	31%
GWP	100%	58%	45%	41%	38%	34%	32%
OLDP	100%	61%	49%	45%	43%	40%	37%
PHOP	100%	52%	40%	36%	34%	31%	29%
CED	100%	56%	43%	39%	37%	34%	31%

*In relation with the tank with the lowest height (2.5 m)
ADP=Abiotic depletion potential, AP=Acidification potential, EP= Eutrophication potential, GWP=Global warming potential, OLDP=Ozone layer depletion potential, PHOP=Photochemical oxidation potential, CED=Cumulative energy demand

a)



b)

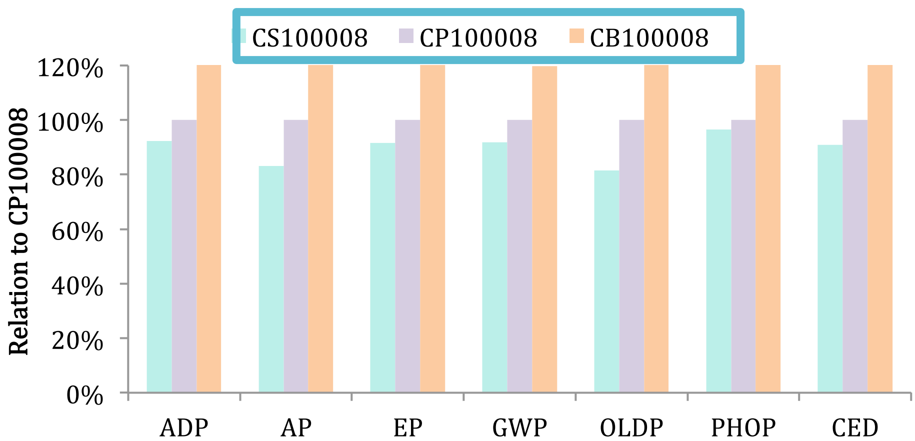


Figure 5.3 Comparison of the environmental impacts of cylindrical water tanks with 8.5 m in height placed buried, partially buried, or superficial for a) 100 m³ and b) 10000 m³

In Figure 5.3.a and 5.3.b only the results of the smallest and the largest of the volumes analysed are included to facilitate representing the results. As shown in Figure 5.3, the environmentally preferable solution is the superficial water tanks. They hold the lowest environmental impacts in all impact categories (between 15 and 35% lower for 100 m³ water tanks and between 20 and 35% for 10,000 m³ water tanks).

This can be explained by the lower requirements in the installation of superficial tanks in contrast with the buried or partially buried configurations. In the superficial tanks, the excavation and transport to landfill of soil operation are not required for its construction, generating lower impacts with the inventory and system established.

5.4.3 Optimization of the capacity

This section aims to find which storage volume holds the lowest amount of environmental impacts. The analysis was made through comparing the impacts generation depending on the storage capacity for each of the volumes analysed.

To narrow the case studies, the comparison was made for the optimal dimension according what have been found in sections 5.4.1 and 5.4.2 (superficial water tank with 8,5 m of height).

Figure 5.4 shows the variation of the impacts generation with the 7 volume cases studied. The graphic shows one curve per impact category evaluated.

As shown in Figure 5.4, the variation of the impacts is not equal for all impact categories. For AP, OLDP and GWP the 2500 m³ tank holds the lowest environmental impacts per cubic meter, being between 15 and 40% higher for tanks smaller than 500 m³. Nevertheless, the environmental impacts are nearly equal (with few differences) from 1,000 m³ to 10,000 m³. For the rest of the impact categories (CED, ADP, EP and PHOP) the lowest environmental impacts correspond to the 1000 m³ water tank, being significantly higher for volumes lower than 500 m³ (between 5 to 30% higher) and larger than 5,000 m³ (between 5 and 20% higher). In this case, volume between 500 and 2,500 m³ present small variations. For this reason, water tank volumes comprised within this range are environmentally preferable, being 1,000 m³ the optimal volume.

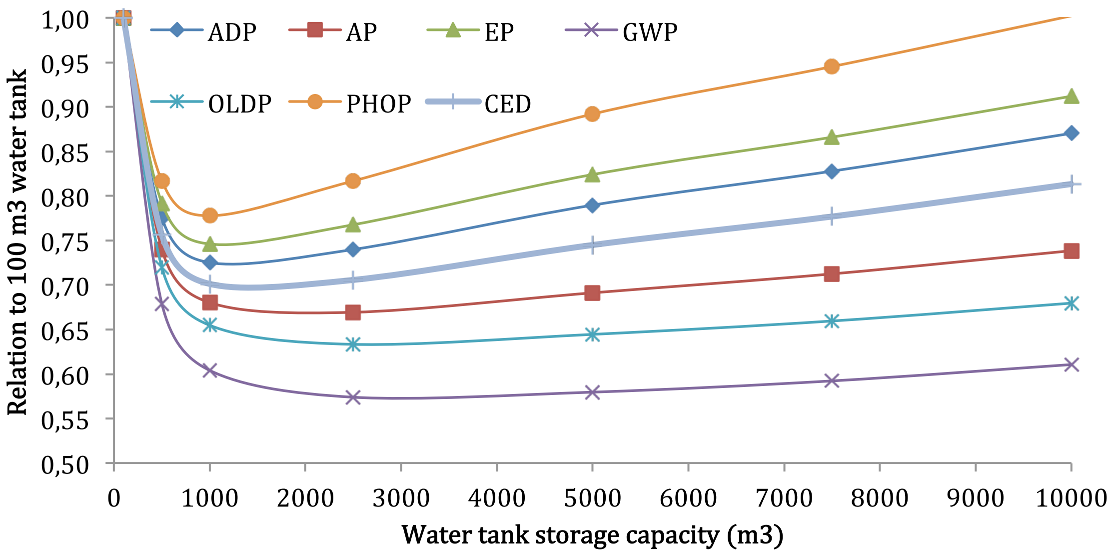


Figure 5.4 Environmental impacts per m³ of storage capacity for each of the water tank volumes analysed

The most influential parameters involved in the generation of the impacts are the relative quantities of concrete and steel.

Figure 5.5 shows the amount of concrete and steel per cubic meter of water storage capacity and along with the ratio of concrete and steel required. It can be observed that whereas the relative amount of concrete is lower for larger volumes, the exact opposite happens with steel, whose relative amount is higher for larger volumes. For this reason, the ratio decreases with the volume of the water tank. This confirms that, as previously mentioned, larger heights and shorter diameters configurations for a given volume provide the minimum perimeter.

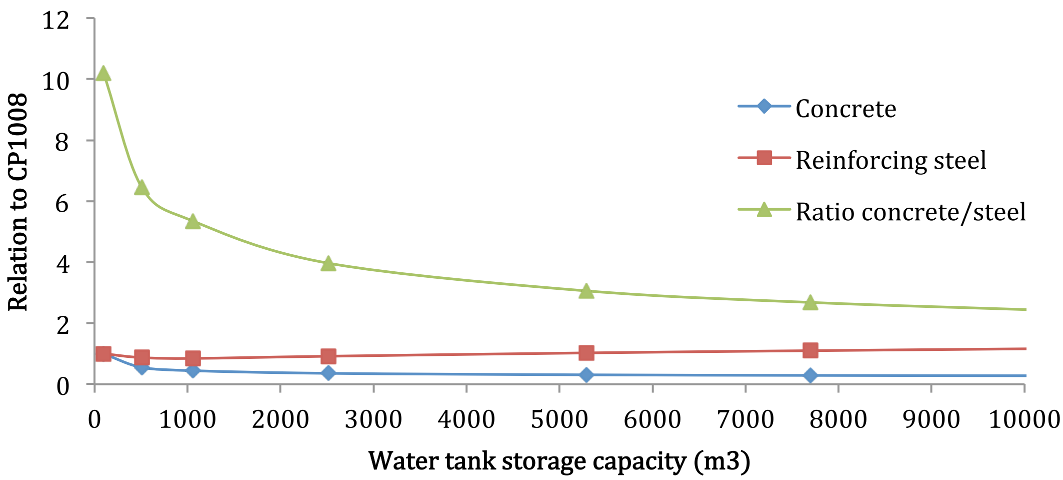


Figure 5.5 Comparison of the quantities of concrete and steel per cubic meter of water storage capacity and the ratio between these materials considering partially buried water tanks with 8.5 m in height

The optimal volumes concluded in this section are 1000 and 2500 m^3 as they hold the lower environmental impacts due to steel quantities, and its relative environmental impacts is higher that those of concrete.

5.5 ENVIRONMENTAL IMPARCTS OF THE WATER TANK ELEMENTS

Figure 5.6 shows the contribution of each life cycle element to the environmental impact of the abiotic depletion potential (ADP) and the global warming potential (GWP) impact categories for the 100 and 10000 m^3 cylindrical partially buried water tanks.. The contribution of each life cycle element to the environmental impacts varies significantly from one impact category to another, so this two (ADP and GWP) have been consider as being the most representative.

For all the options, steel and concrete account for most of the impacts of the water tanks (between 70 and 80% of the impact). The contribution of steel to the environmental impacts of ADP is higher than for GWP (around 50% and 75% for ADP as opposed to 30 and 60% for GWP). Also, for water tanks with larger storage capacities the contribution of steel is greater (nearly 60% for 10,000 m^3 as opposed to 30% for 100 m^3 for GWP).

These results support what was stated in section 5.4.3, the differences found for the different volumes and impact categories are due to the variations in the requirements of steel and concrete, which hold different types of environmental impacts.

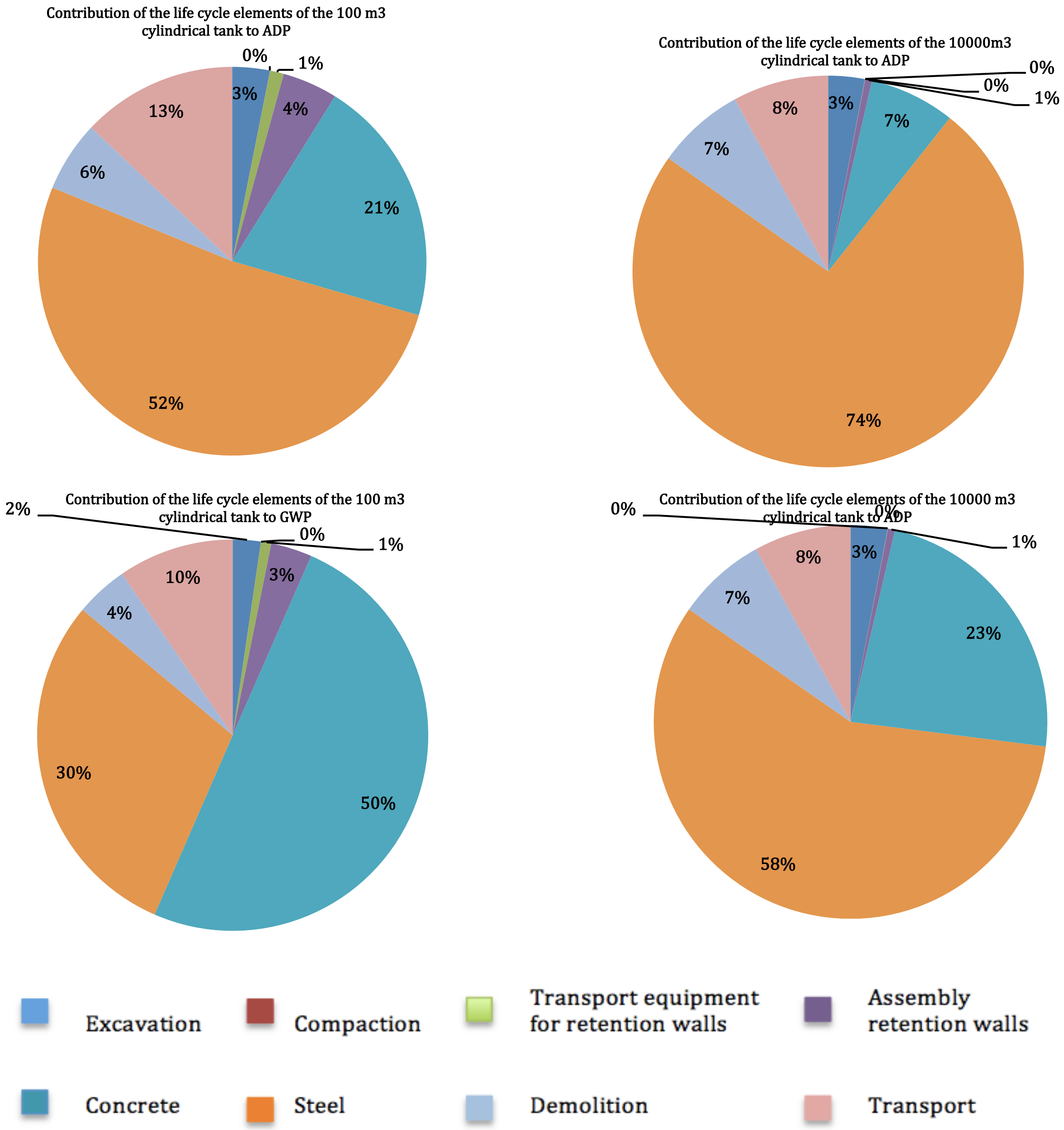


Figure 5.6 Contribution of each life cycle element to the environmental impacts of ADP and GWP of 100 and 10,000 m3 cylindrical partially buried water tanks

CHAPTER 6

CONCLUSIONS

6.1 GENERAL CONCLUSIONS

In this section the general conclusion are presented in response to the general objectives defined in Chapter 1, which guided the development of this study. Furthermore, to give a general idea of the accomplishments obtained, in section 6.2 the specific conclusions are listed following the logical sequence of the work performed.

A range of different volumes and under different shape typologies has been studied. In the structural analysis, 7056 different case studies were assessed depending on the dimensions, the position on the ground, the wall thickness, the amount of armor and the water storage capacity. The parameters considered have been narrowed in order to provide a range that optimizes the design from the structural point of view.

Cylindrical water tanks require less materials consumption than rectangular configurations due to their geometry, which allows minimizing the perimeter for a given volume.

Even tough all cases analyzed that meet the criteria established by the code could be considered valid and optimal since they are dimensioned to cope with the loads applied, the criteria in order to choose the optimal configuration between the different solutions will be provided y the environmental analysis through the LCA methodology.

With the geometrical typology and wall thickness set, the LCA carried out in this work revealed that tanks configured with larger heights and built in the surface are the optimal solution, as their construction generates the lower amount of environmental impacts.

6.2 SPECIFIC CONCLUSIONS

Several specific objectives are defined in Chapter 1 for each of the subjects studied in this work. In response to these specific objectives, the contributions made are described in detail in the several chapters of this document. To provide a general overview of the contributions made through this work, the main specific conclusions of each subject addressed are presented next.

Structural design

Wall thickness

After studying a large range of thickness values to find which of them should be fixed as the standard one for all the cases proceed, the value that provides the best design in terms of less materials consumption is a wall thickness of 30 cm, which is also the minimum value recommended by previous studies and standards in order to perform a proper construction of the tank.

Optimal geometrical configuration for a given volume

Regarding the best geometrical configuration in the rectangular typology, each volume evaluated has associated a particular configuration that requires the less material consumption, all of them with heights between 4 and 2 m and shown in chapter 4. In the case of the cylindrical typology, it is shown that the lower requirements of concrete and reinforcing steel for its construction of water tanks are the configurations set with 8 m in height for all volumes evaluated.

After concluding that, through comparing the results of the optimal configurations for both typologies in each volume studied, and evaluating the evolving of the materials consumption with the range of volumes established, it is concluded that the geometrical configuration which provides a better optimization of the materials is the cylindrical one for all volumes analyzed.

Armor ratios

Through studying the variation of the reinforcement required for the design by setting different design reinforcement ratios for the different capacities established, it is concluded that for the partially buried and surface typologies, the efforts generated in the walls are not reliable when it comes to solve the design, in order to arrange the required reinforcement, prevails the SLS for cracking criteria. In the buried typology prevails the strict amount of reinforcement to cope with the efforts above the minimum ratios as the volume studied increases, that is because the efforts seeking the walls become higher due to the tension produced by the buoyancy and the compression resulted from the soil pressure.

Position of the tank

Based on the comparison of the evolving materials consumption with the geometrical configurations established for every typology studied according to the different positions of the tank, it is concluded that the configuration which requires the higher materials consumption is the buried one, while the optimal choice in terms of less materials consumption is the partially buried typology. This result becomes more significant with higher water storage capacities.

Life Cycle Assessment (LCA)

Within the system boundaries of the construction phase set in the LCA analysis, a general overview of the study reveals that the relative quantities of steel and concrete are the life cycle elements which account for the most of the impacts generated in the water tanks (between 70 and 80% of the impact).

Regarding the geometrical configuration of the tank, the analysis shows that the results presented in the structural study are the best options to choose for designing (8 m in height for all cases studied), as this configurations comes to be the ones that generates less impacts.

As for the position of the tank, the LCA reveals that the environmental preferable solution is the superficial water tanks, as they hold the lowest values in all impact categories. The disagreement with the structural results is due to the inventory system established in the LCA study, in which features such as the installation and transport of materials are taken into account to provide the optimal solution. Based on that, in surface tanks, the excavation and transport to landfill of soil operation are not required for its construction, generating lower impacts.

Finally, the environmental study reveals that within the range of volumes studied, the optimal volumes are 1000 and 2500 m^3 as they hold the lower environmental impacts due to the relation of materials quantities.

6.3 FINAL RECOMMENDATIONS

In spite of the contributions reported in the previous section, further research on interesting topics still remains. Based on that, this section includes the future perspectives of the topics treated in this work. Below are the possible lines of research with which to continue the work in this field.

The study conducted showed the structural behavior and LCA of water tanks. However, due to the wide variety of shapes and typologies configurations, it might be interesting to extend the analyses to other reinforcement materials and dimensions.

Furthermore, the same structural study with prestressed concrete and with fibre-reinforced concrete (FRC) as alternative reinforcement materials could be done. Also, a detailed study playing with the different arrangements and configurations of the internal walls in rectangular shapes could be interesting in order to expand the study performed.

Finally, as mentioned in chapter 2, the concept of sustainability includes 3 bases, the environmental, the economic and social. The economic and social impacts generated by this structure should be analyzed in order to provide a full sustainable solution.

REFERENCES

ACI 224.1R-93. *Causes, Evaluation and Repair of Cracks in Concrete Structures*. Manual of Concrete Practice (pp. 1–22). 1998. ACI. doi:ISBN: 978 0 87031 234 2

AEAS. *Recomendaciones sobre depósitos de agua potable. 1a edición*, Asociación Española de abastecimiento de agua y saneamiento. 1990

Aimar Orbe, M. *"Optimización del uso de Hormigones Autocompactantes Reforzados con Fibras de Acero en Aplicaciones Convencionales de Resistencias Moderadas".* Tesis Doctoral. Universidad del País Vasco, 2013.

AWWA. *Modeling, Analysis, and Design of Water Distribution Systems.* American Water Works Association. 1995

Amores, M. J., Meneses, M., Pasqualino, J., Antón, A., & Castells, F. *Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach.* Journal of Cleaner Production, 43, 84–92, 2013.

Anchor, R. D. *Design of liquid retaining concrete structures*. Second edition. McGraw-Hill. New York, 1992.

Barés, R. *Tablas para el cálculo de placas y vigas pared*. Gustavo Gili. Barcelona, 1981.

BS 8007 *"Design of Concrete Structures for Retaining Aqueous Liquids",* British Standars Institution, 1987.

Calavera Ruiz, J. *Proyecto y cálculo de Estructuras de hormigón*, Tomo II, Ed. INFOPRINT, S.A, 1999.

CEDEX. *Guía técnica sobre depósitos para abastecimiento de agua potable*. Centro de Publicaciones del Ministerio de Fomento, 2010. ISBN : 978-84-7790-513-4.

Canales & Taibilla, (n.d.) Guía para el diseño y proyecto de depósitos.

Del Borghi, A., Strazza, C., Gallo, M., Messineo, S., & Naso, M. *Water supply and sustainability: Life cycle assessment of water collection, treatment and distribution service*. International Journal of Life Cycle Assessment, 2013.

Dilger, W. H. *Reinforced concrete: mechanics and design*. Canadian Journal of Civil Engineering. doi:10.1139/l00-087, 2000.

Ecoinvent. *Swiss Centre for Life Cycle Inventories*. *Ecoinvent database v3.0.* Technical report., 2009. Avaiable: <http://www.ecoinvent.ch>

EHE (2008) *Instrucción de hormigón estructural*. Comisión Permanente del Hormigón, Ministerio de Fomento.

European Committee for Standaritzation. *EuroCodigo-2*, 2003.

EPA. *Finished Water Storage Facilities.* Environmental Protection Agency, 2002.

EN 15804 *Sustainability of Construction Works e Environmental Product Declarations e Core Rules for the Product Category of Construction Product*. European Committee for Standardization, 2011.

García Messeguer, A. *Hormigón armado I. Materiales. Ejecución. Control. Patología*. Universidad Nacional de educación a distancia, fundación escuela de la edificación, 2001.

González G. Zabaleta, G. *Cálculo y construcción de depósitos*. CEAC. Barcelona, 1986.

Hernández Muñoz, A. *Abastecimiento y distribución de aguas*. 4a ed. Colección Seinor no 6. Colegio de Ingenieros de Caminos, Canales y Puertos, 2000. 914 p. ISBN: 84-380-0165-3

ILCD Handbook. *International Reference Life Cycle Data System. General Guide for Life Cycle Assessment – Detailed Guidance.* First edition. Joint Research Centre – Institute for Environmental and Sustainability, 2010.

INTEMAC *Curso de Depósitos, tanques y balsas (Proyecto y ejecución).* Cursos de especialización, 2007.

INTEMAC *Curso de Proyecto, cálculo, detalles constructivos, ejecución y patologías de depósitos de hormigón armado.* Cursos de especialización, 2012.

ISO 14040 *Environmental management - Life cycle assessment - Principles and framework.* International Organization for Standardarization, 2006.

ISO 15686 *Buildings and constructed assets - Service-life planning - Life cycle costing.* International Organization for Standardarization, 2008.

Jiménez Montoya, P., García Meseguer, Á., & Morán Cabré, F. *Hormigón armado*. 14ª ed. Gustavo Gili. Barcelona, 2004.

Kia, S., Reza, M. *Modeling and shape optimization of reinforced concrete reservoirs using Particle Swarm Algorithm.* International Journal of Civil and Structural Engineering, 2(4), 0976-4399, 2012.

Lemos, D., Dias, A. C., Gabarrell, X., & Arroja, L. *Environmental assessment of an urban water system.* Journal of Cleaner Production, *54*, 157–165, 2013.

Mendoza, J. M. F., Oliver-Solà, J., Gabarrell, X., Rieradevall, J., & Josa, A. *Planning strategies for promoting environmentally suitable pedestrian pavements in cities.* Transportation Research Part D: Transport and Environment, 17(6), 442–450, 2012.

Metabase ITeC. *Online ITeC Database: Prices, Technical Details, Companies, Certificates, Product Pictures and Environmental Data*. 2010 Retrieved from: http://www.itec.cat/metabase

Mosley, W. H., Bungey, J. H., & Hulse, R. *Reinforced concrete design to Eurocode 2.* (R. Hulse & J. H. Bungey, Eds.)Civil Engineering (p. 408). Palgrave MacMillan, 2007.

Murcia Vela, J., Aguado de Cea, A. y Marí Bernat, A.R. *Hormigón Armado y pretensado – I.* Edicions UPC. Barcelona, 1993.

Piratla, K. R., Asce, S. M., Ariaratnam, S. T., Asce, M., & Cohen, A. (2012). *Estimation of CO_2 Emissions from the Life Cycle of a Potable Water Pipeline Project*, 22–30. doi:10.1061/(ASCE)ME.1943-5479.0000069. January, 2012.

Pozo, F. del. *Depósitos cilíndricos circulares*. Laboratorio Central de Ensayo de Materiales de Construcción. Madrid, 1967.

Riba Genescà, E. "*Cálculo y elección óptima de un depósito de agua"*. Director: Antonio Aguado. Universitat Politècnica de Catalunya. Departament de Resistència de Materials i Estructures a l'Enginyeria, Barcelona, 2006.

Sanjuan-Delmás, D., Petit-Boix, A., Gasol, C. M., Villalba, G., Suárez-Ojeda, M. E., Gabarrell, X., Rieradevall, J. *Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain.*Journal of Cleaner Production, 66, 588–598, 2014.

Serea, V. I., & Urbano, A. *Representación de diferentes tipologías de depósitos mediante el modelo epanet*. 6th Seminario Iberoamericano sobre Sistemas de Abastecimiento Urbano de Agua. Joao Pessoa, Brasil. June, 2006.

Venkatesh, G., & Brattebø, H. *Energy consumption, costs and environmental impacts for urban water cycle services: Case study of Oslo (Norway).* Energy, 36(2), 792–800, 2011

Venkatesh, G., & Brattebø, H. *Environmental Impact Assessment, Theory & Practice*. Water science and technology : a journal of the International Association on Water Pollution Research (Vol. 63, pp. 1019–32), 2011.

Viñolas, B. *Applications admethodology advances in MIVES multicriteria valorations (Aplicaciones y avances de la metodología MIVES en valoraciones multicriterio).* Doctoral thesis. Universitat Politècnica de Catalunya, Barcelona, 2011.

Walski, T.M. *"Hydraulic Design of Water Distribution Storage Tanks". Chapter 10* in Water Distribution Systems Handbook, Edited by L.W. Mays, New York. NY: McGraw-Hill, 2000.

APPENDIX A

CALCULATION PROGRAM AND STRUCTURAL PARAMETRIC STUDY RESULTS

1. INTRODUCTION

The aim of this appendix is to present the two programs developed in the present work along with all the cases and the absolute structural results.

The calculation program is designed in accordance with the calculation methodology detailed in chapter 3. There are two excel documents attached to this document corresponding to the typologies studied, rectangular concrete tanks and cylindrical reinforced concrete tanks. Regarding the structural results, two other excel documents are presented also according to both typologies.

Doc 1: *Rectangular tanks program*
Doc2: *Cylindrical tanks program*

Doc3: *Rectangular tanks study*
Doc4: *Cylindrical tanks study*

2. RESULTS TO PROVIDE THE BEST CONFIGURATION FOR A GIVEN VOLUME

In tables B.1 and B.2 there are shown the numerical results for the rectangular and cylindrical tanks typologies depending on the geometrical configuration, according to the general results shown in tables 4.3 and 4.4 of Chapter 4. As mentioned in chapter 4, the wall thickness is fixed with a value of 30 cm in order to delimitate the parameters evaluated and to provide standards results.

Table A.1 Cylindrical reinforced concrete materials consumption results

Cylindrical Reinforced Concrete Tanks

100 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; R=4,00)	576,7	11896	576,7	11896	576,7	11896
C_2 (a=3,00 ; R=3,30)	490,7	8198	490,7	8198	490,7	8198
C_3 (a=4,00 ; R=3,00)	460,1	6806	460,1	6806	460,1	6806
C_4 (a=5,00 ; R=2,60)	415,7	5253	415,7	5253	415,7	5253
C_5 (a=6,00 ; R=2,40)	399	4626	399	4626	399	4626
C_6 (a=7,00 ; R=2,20)	390,9	4117	390,9	4117	390,9	4117
C_7 (a=8,00 ; R=2,00)	384	3725	384	3725	384	3725

500 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; R=9,00)	1270	59899	1270	59899	1270	59899
C_2 (a=3,00 ; R=7,50)	1073,1	41657	1073,1	41657	1073,1	41657
C_3 (a=4,00 ; R=6,50)	946,7	31491	946,7	31491	946,7	31491
C_4 (a=5,00 ; R=5,70)	869,7	24384	869,7	24384	869,7	24384
C_5 (a=6,00 ; R=5,20)	840,3	20660	840,3	20660	840,3	20660
C_6 (a=7,00 ; R=4,80)	830	18101	830	18101	830	18101
C_7 (a=8,00 ; R=4,50)	838,5	16424	838,5	16424	838,5	16424

1000 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; R=13,00)	1824,7	125037	1824,7	125037	1824,7	125037
C_2 (a=3,00 ; R=10,50)	1489,1	81563	1489,1	81563	1489,1	81563
C_3 (a=4,00 ; R=9,00)	1300,3	60045	1300,3	60045	1300,3	60045
C_4 (a=5,00 ; R=8,00)	1206,9	47848	1206,9	47848	1206,9	47848
C_5 (a=6,00 ; R=7,50)	1194,8	42365	1194,8	42365	1194,8	42365
C_6 (a=7,00 ; R=7,00)	1189,9	37571	1189,9	37571	1189,9	37571
C_7 (a=8,00 ; R=6,50)	1189,8	33293	1189,8	33293	1189,8	33293

2500 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; R=20,00)	2795,3	295966	2941,2	311389	2795,3	295966
C_2 (a=3,00 ; R=16,50)	2321	201283	2321	201283	2321	201283
C_3 (a=4,00 ; R=14,50)	2069,1	155694	2069,1	155694	2069,1	155694
C_4 (a=5,00 ; R=13,00)	1926,6	125526	1926,6	125526	1926,6	125526
C_5 (a=6,00 ; R=12,00)	1952,8	112683	1952,8	112683	1952,8	112683
C_6 (a=7,00 ; R=11,00)	1963,3	99348	1963,3	99348	1965,2	99416
C_7 (a=8,00 ; R=10,00)	1950,5	85434	1950,5	85434	1981,4	87061

5000 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; R=28,50)	4147,7	626475	5075,1	767539	3974	600303
C_2 (a=3,00 ; R=23,50)	3291,7	408396	3715,2	461346	3291,7	408396
C_3 (a=4,00 ; R=20,00)	2830,2	296127	2945,3	308297	2830,2	296127
C_4 (a=5,00 ; R=18,00)	2803,5	256293	2803,5	256293	2803,5	256293
C_5 (a=6,00 ; R=16,50)	2856,4	230969	2856,4	230969	2946,9	238922
C_6 (a=7,00 ; R=15,50)	2976,1	217458	2976,1	217458	3170,4	233427
C_7 (a=8,00 ; R=14,50)	3070,5	200938	3070,5	200938	3337,6	221554

7500 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; R=35,00)	5750	1068255	7617,8	1416384	4875,3	905050
C_2 (a=3,00 ; R=28,50)	3985	600350	5054,9	762779	3985	600350
C_3 (a=4,00 ; R=24,50)	3473	446680	3976,2	512364	3473	446680
C_4 (a=5,00 ; R=22,00)	3552,2	400480	3800,5	429506	3619,1	408299
C_5 (a=6,00 ; R=20,00)	3616,3	358965	3700,7	367881	3861,7	385112
C_6 (a=7,00 ; R=18,50)	3717,6	328672	3717,6	328672	4094,2	365675
C_7 (a=8,00 ; R=17,50)	3902,4	313606	3902,4	313606	4396,6	359679

10000 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; R=40,00)	7693,7	1635106	10235,2	2181129	6266,3	1331227
C_2 (a=3,00 ; R=33,00)	4649,1	820777	6734,2	1178438	4609	804872
C_3 (a=4,00 ; R=28,50)	4093,1	614685	5131,8	772306	4093,1	614685
C_4 (a=5,00 ; R=25,50)	4232,3	556282	4820,1	636168	4410,1	580401
C_5 (a=6,00 ; R=23,50)	4422,3	520592	4782,2	565613	4870,9	576656
C_6 (a=7,00 ; R=21,50)	4508,9	468804	4681,7	488493	5158,5	543024
C_7 (a=8,00 ; R=20,00)	4645,7	432388	46998,	438050	5458,6	518900

Table B.2 Rectangular reinforced concrete materials consumption results

Rectangular reinforced concrete tanks

100 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; b_1=7,50; b_2=3,50)	549,6	549,6	549,6	5311,4	549,6	549,6
C_2 (a=3,00 ; b_1=5,50; b_2=3,00)	510,7	510,7	510,7	3637,4	510,7	510,7
C_3 (a=4,00 ; b_1=5,00; b_2=2,50)	548,3	548,3	548,3	3850,2	548,3	548,3
C_4 (a=5,00 ; b_1=4,50; b_2=2,50)	642,1	642,1	642,1	4564,1	642,1	642,1
C_5 (a=6,00 ; b_1=4,50; b_2=2,00)	907,0	907,0	925,4	7671,2	907,0	907,0
C_6 (a=7,00 ; b_1=4,00; b_2=2,00)	1133,3	1133,3	1241,6	11373,5	1133,3	1133,3

C_7 (a=8,00 ; b_1=3,50; b_2=2,00)	1410,1	1410,1	1727,6	17399,88	1410,1	1410,1

500 m³	Partially Buried		Surface		Buried	
	cm²	kg	cm²	kg	cm²	kg
C_1 (a=2,00 ; b_1=15,00; b_2=8,50)	1030,5	21034,1	1030,5	21034,1	1030,5	21034,1
C_2 (a=3,00 ; b_1=17,00; b_2=5,00)	1156,4	24885,4	1156,4	24885,4	1156,4	24885,4
C_3 (a=4,00 ; b_1=12,50; b_2=5,00)	1032,4	15358,7	1032,4	15358,7	1032,4	15358,7
C_4 (a=5,00 ; b_1=10,00; b_2=5,00)	1158,4	14356,4	1158,4	14356,4	1158,4	14356,4
C_5 (a=6,00 ; b_1=9,50; b_2=4,50)	1484,4	18319,0	1484,4	18319,0	1523,8	18890,3
C_6 (a=7,00 ; b_1=9,00; b_2=4,00)	1824,6	22684,3	1824,6	22684,3	1992,5	24873,5
C_7 (a=8,00 ; b_1=8,00; b_2=4,00)	2197,0	27071,3	2197,0	27071,3	2668,4	33100,9

1000 m³	Partially Buried		Surface		Buried	
	cm²	kg	cm²	kg	cm²	kg
C_1 (a=2,00 ; b_1=25,50; b_2=10,00)	1577,1	55541,2	1577,1	55541,2	1577,1	55541,2
C_2 (a=3,00 ; b_1=19,00; b_2=9,00)	1352,8	32693,8	1352,8	32693,8	1352,8	32693,8
C_3 (a=4,00 ; b_1=14,00; b_2=9,00)	1209,8	20850,5	1209,8	20850,5	1209,8	20850,5
C_4 (a=5,00 ; b_1=20,00; b_2=5,00)	1900,0	44865,4	1900,0	44865,4	1900,0	44865,4
C_5 (a=6,00 ; b_1=17,00; b_2=5,00)	2232,0	44881,6	2232,0	44881,6	2297,3	46643,0
C_6 (a=7,00 ; b_1=14,50; b_2=5,00)	2532,5	44567,3	2532,5	44567,3	2759,8	49007,2
C_7 (a=8,00 ; b_1=12,50; b_2=5,00)	2930,0	47094,5	2930,0	47094,5	3541,3	57706,6

2500 m³	Partially Buried		Surface		Buried	
	cm²	kg	cm²	kg	cm²	kg
C_1 (a=2,00 ; b_1=42,00; b_2=15,00)	2497,0	147409,2	2497,0	147409,2	2497,0	147409,2
C_2 (a=3,00 ; b_1=28,00; b_2=15,00)	1438,9	35486,6	1438,9	35486,6	1438,9	35486,6
C_3 (a=4,00 ; b_1=32,00; b_2=10,00)	2256,5	87593,4	2256,5	87593,4	2256,5	87593,4
C_4 (a=5,00 ; b_1=26,00; b_2=10,00)	2484,6	75915,4	2484,6	75915,4	2484,6	75915,4
C_5 (a=6,00 ; b_1=21,00; b_2=10,00)	2803,3	69257,2	2803,3	69257,2	2890,4	72041,4
C_6 (a=7,00 ; b_1=18,00; b_2=10,00)	3174,2	68298,1	3174,2	68298,1	3440,1	74749,0
C_7 (a=8,00 ; b_1=16,00; b_2=10,00)	3727,5	74093,4	3727,5	74093,4	4476,4	90539,6

5000 m³	Partially Buried		Surface		Buried	
	cm²	kg	cm²	kg	cm²	kg
C_1 (a=2,00 ; b_1=51,00; b_2=25,00)	3166,3	228631,7	3166,3	228631,7	3166,3	228631,7
C_2 (a=3,00 ; b_1=42,00; b_2=20,00)	2805,5	155479,0	2805,5	155479,0	2805,5	155479,0
C_3 (a=4,00 ; b_1=42,00; b_2=15,00)	2940,4	150769,1	2940,4	150769,1	2940,4	150769,1
C_4 (a=5,00 ; b_1=32,00; b_2=15,00)	3224,8	129849,5	3224,8	129849,5	3224,8	129849,5

C_5 (a=6,00 ; b_1=28,00; b_2=15,00)	3666,4	121087,4	3666,4	121087,4	3785,3	126231,5
C_6 (a=7,00 ; b_1=24,00; b_2=15,00)	4117,8	117310,7	4117,8	117310,7	4488,9	129546,0
C_7 (a=8,00 ; b_1=32,00; b_2=10,00)	6142,3	222904,4	6142,3	222904,4	7369,2	276389,3

7500 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; b_1=63,00; b_2=30,00)	4143,1	380522,9	4143,1	380522,9	4143,1	380522,9
C_2 (a=3,00 ; b_1=51,00; b_2=25,00)	3390,0	230019,5	3390,0	230019,5	3390,0	230019,5
C_3 (a=4,00 ; b_1=47,00; b_2=20,00)	3339,9	193135,3	3339,9	193135,3	3339,9	193135,3
C_4 (a=5,00 ; b_1=38,00; b_2=20,00)	3664,7	167089,0	3664,7	167089,0	3664,7	167089,0
C_5 (a=6,00 ; b_1=42,00; b_2=15,00)	5027,8	245230,2	5027,8	245230,2	5193,6	256011,8
C_6 (a=7,00 ; b_1=36,00; b_2=15,00)	5566,7	228505,3	5566,7	228505,3	6056,7	252891,7
C_7 (a=8,00 ; b_1=32,00; b_2=15,00)	6411,6	234334,1	6411,6	234334,1	7659,1	288758,5

10000 m^3	Partially Buried		Surface		Buried	
	cm^2	kg	cm^2	kg	cm^2	kg
C_1 (a=2,00 ; b_1=72,00; b_2=35,00)	4420,7	454211,3	4420,7	454211,3	4420,7	454211,3
C_2 (a=3,00 ; b_1=56,00; b_2=30,00)	3765,9	283312,1	3765,9	283312,1	3765,9	283312,1
C_3 (a=4,00 ; b_1=51,00; b_2=25,00)	3682,5	232481,9	3682,5	232481,9	3682,5	232481,9
C_4 (a=5,00 ; b_1=51,00; b_2=20,00)	4628,9	280991,2	4628,9	280991,2	4628,9	280991,2
C_5 (a=6,00 ; b_1=42,00; b_2=20,00)	5384,4	267364,8	5384,4	267364,8	5384,4	267364,8
C_6 (a=7,00 ; b_1=36,00; b_2=20,00)	5785,8	241536,6	5785,8	241536,6	6263,9	265558,0
C_7 (a=8,00 ; b_1=32,00; b_2=20,00)	6680,9	250365,6	6680,9	250365,6	6300,7	267360,5

3. RESULTS DEPENDING ON THE WALL THICKNESS

In figures B.1, B.2, B.3, B.4 and B.5, the result regarding the steel amount variation depending on the different wall thickness is presented. The figures correspond to the surface and buried configurations for both cylindrical and rectangular typologies.

CYLINDRICAL SURFACE TANKS

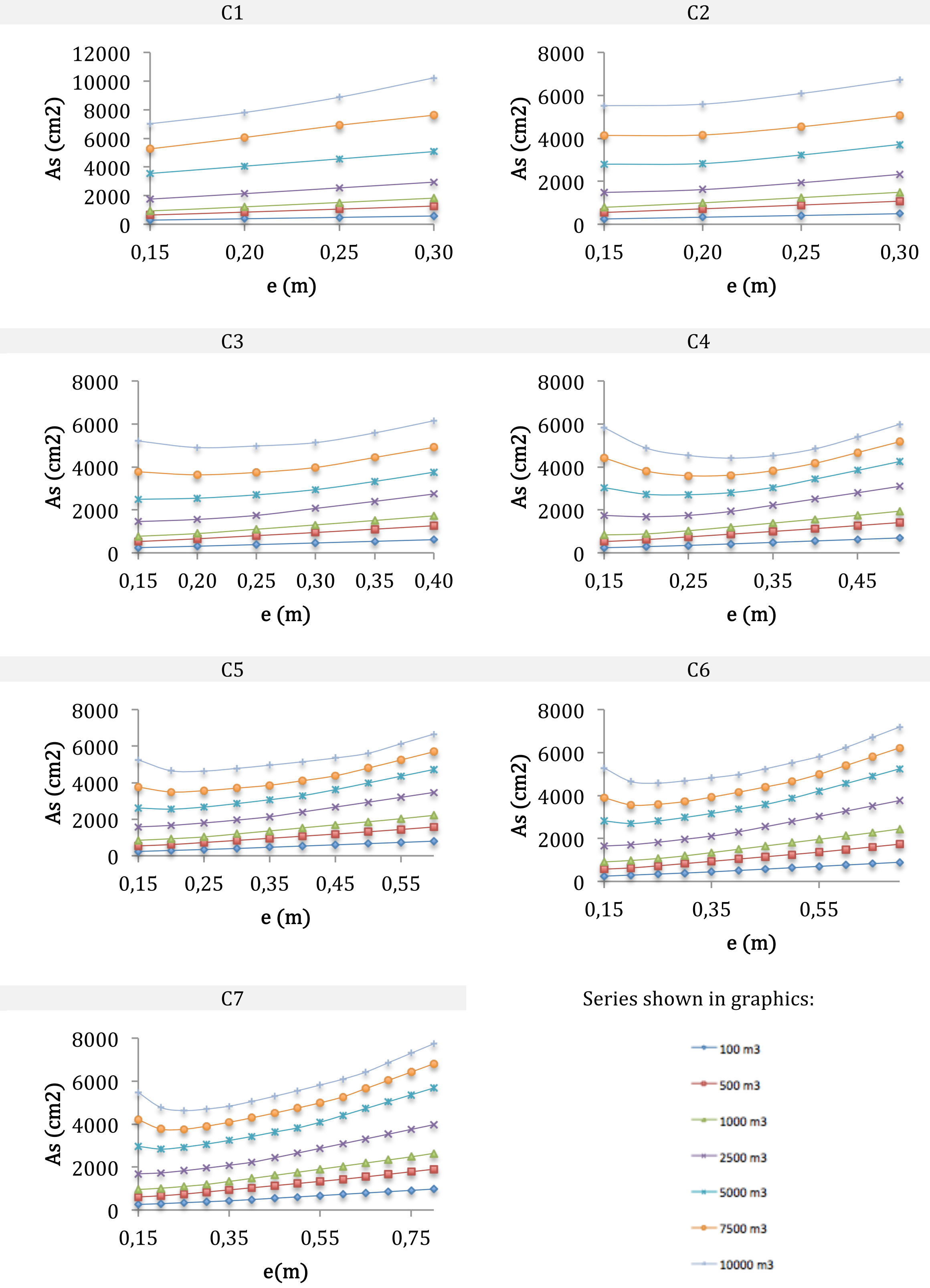


Figure B.1 A_s f(e) Reinforcement ratio variation depending on the wall thicknesses evaluated for each volume in Cylindrical surface tanks

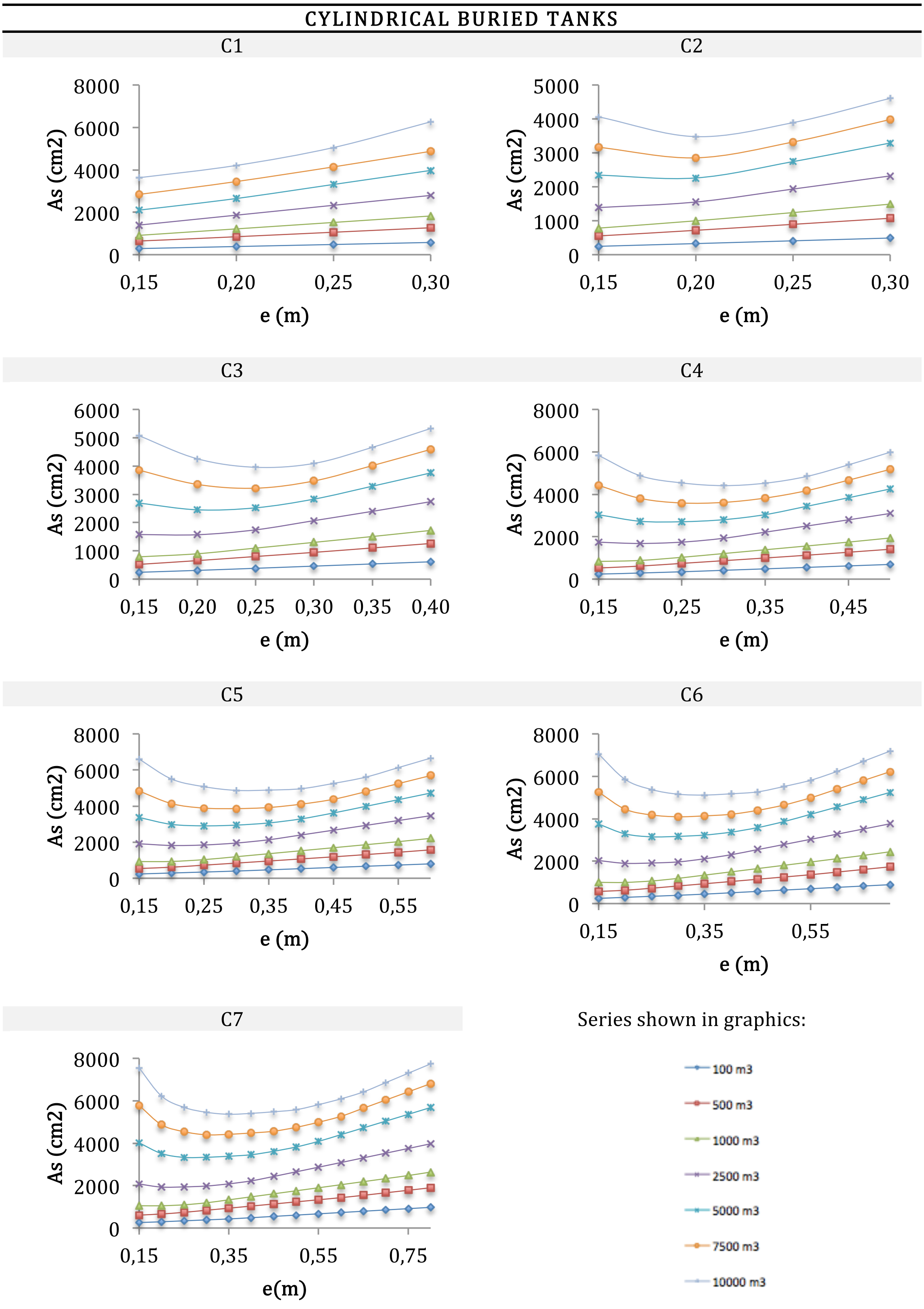


Figure B.2 A_s f(e) Reinforcement ratio variation depending on the wall thicknesses evaluated for each volume in Cylindrical buried tanks

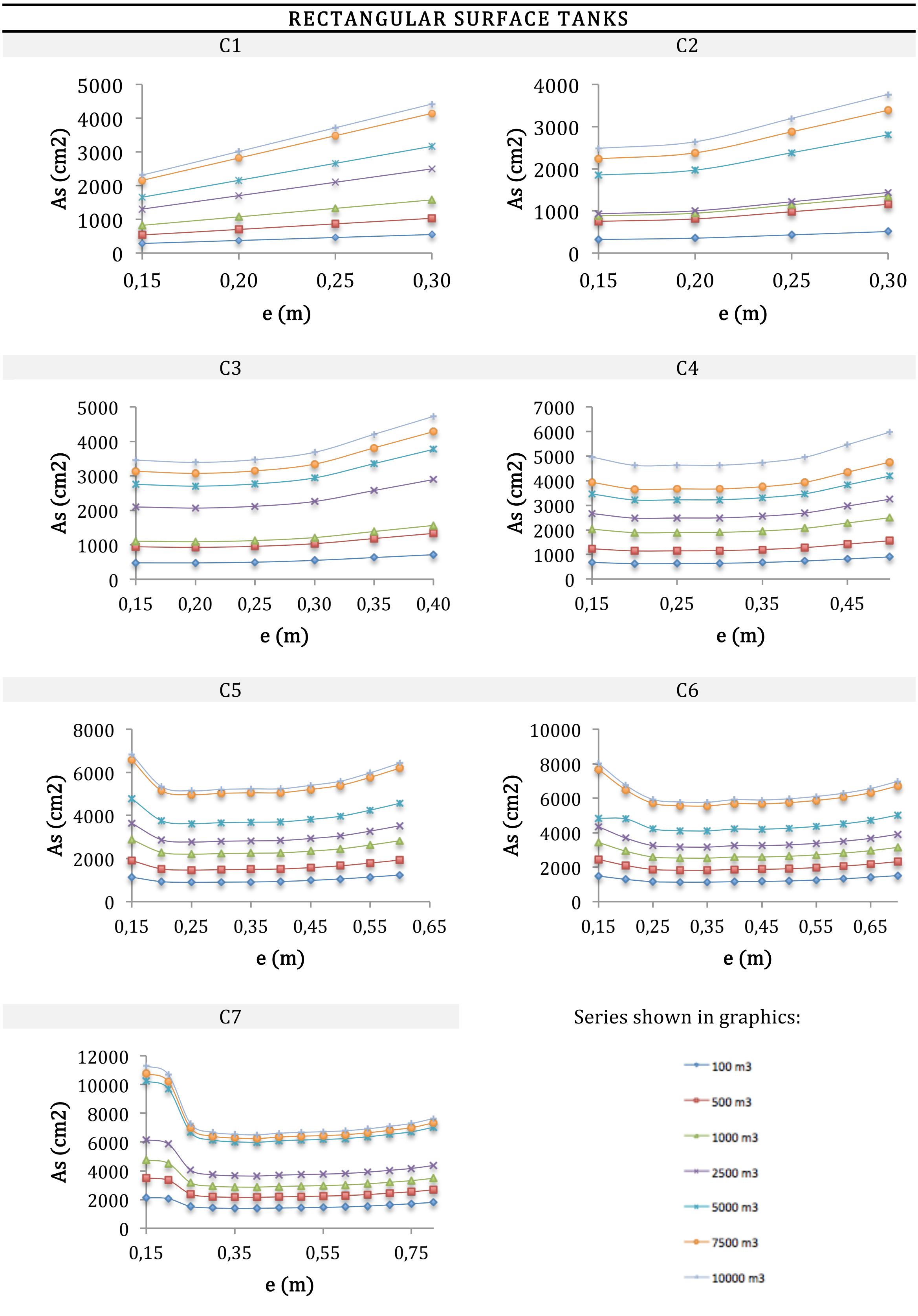


Figure B.3 A_s f(e) Reinforcement ratio variation depending on the wall thicknesses evaluated for each volume in Rectangular surface tanks

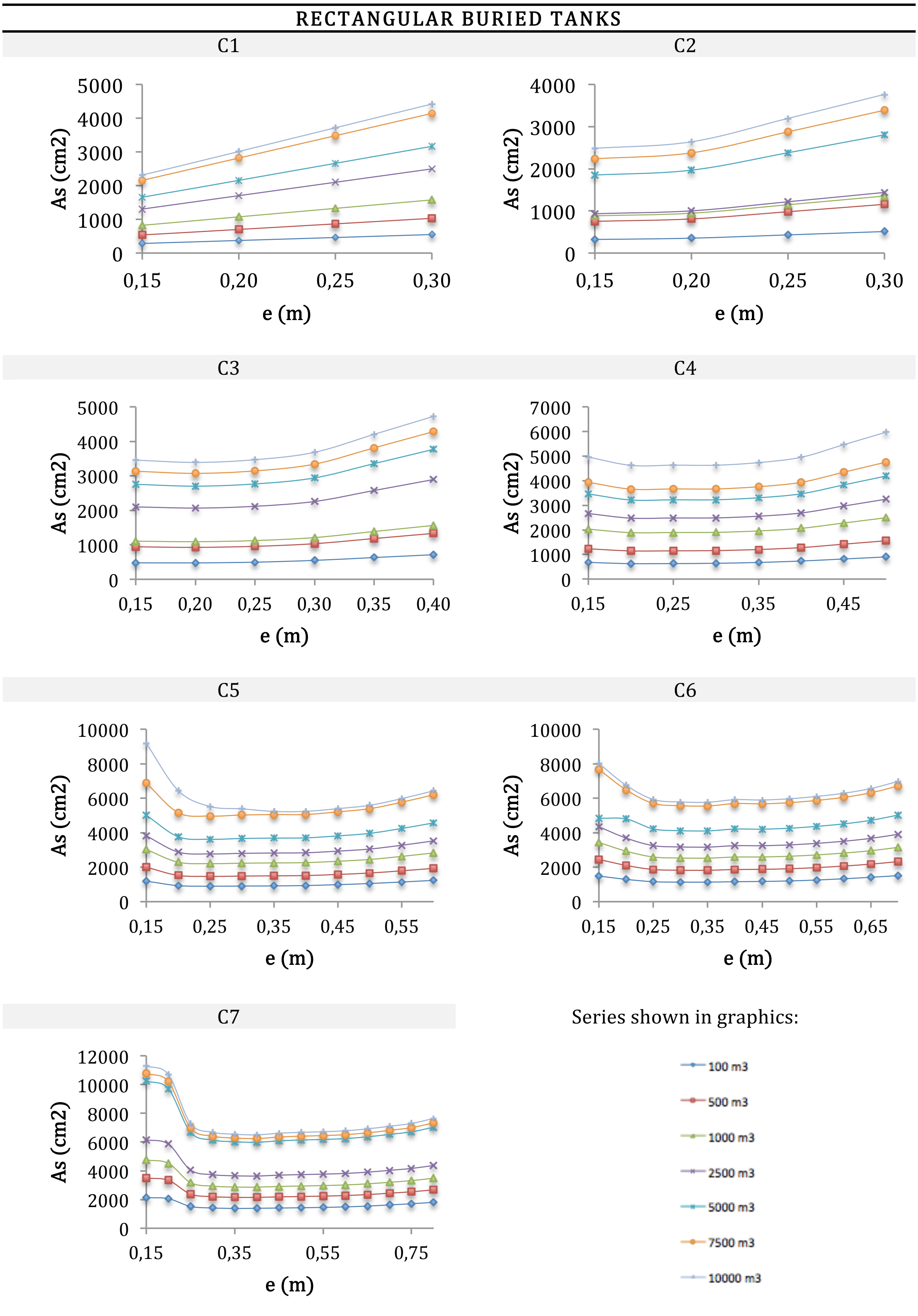


Figure B.4 $A_s\,f(e)$ Reinforcement ratio variation depending on the wall thicknesses evaluated for each volume in Rectangular buried tanks

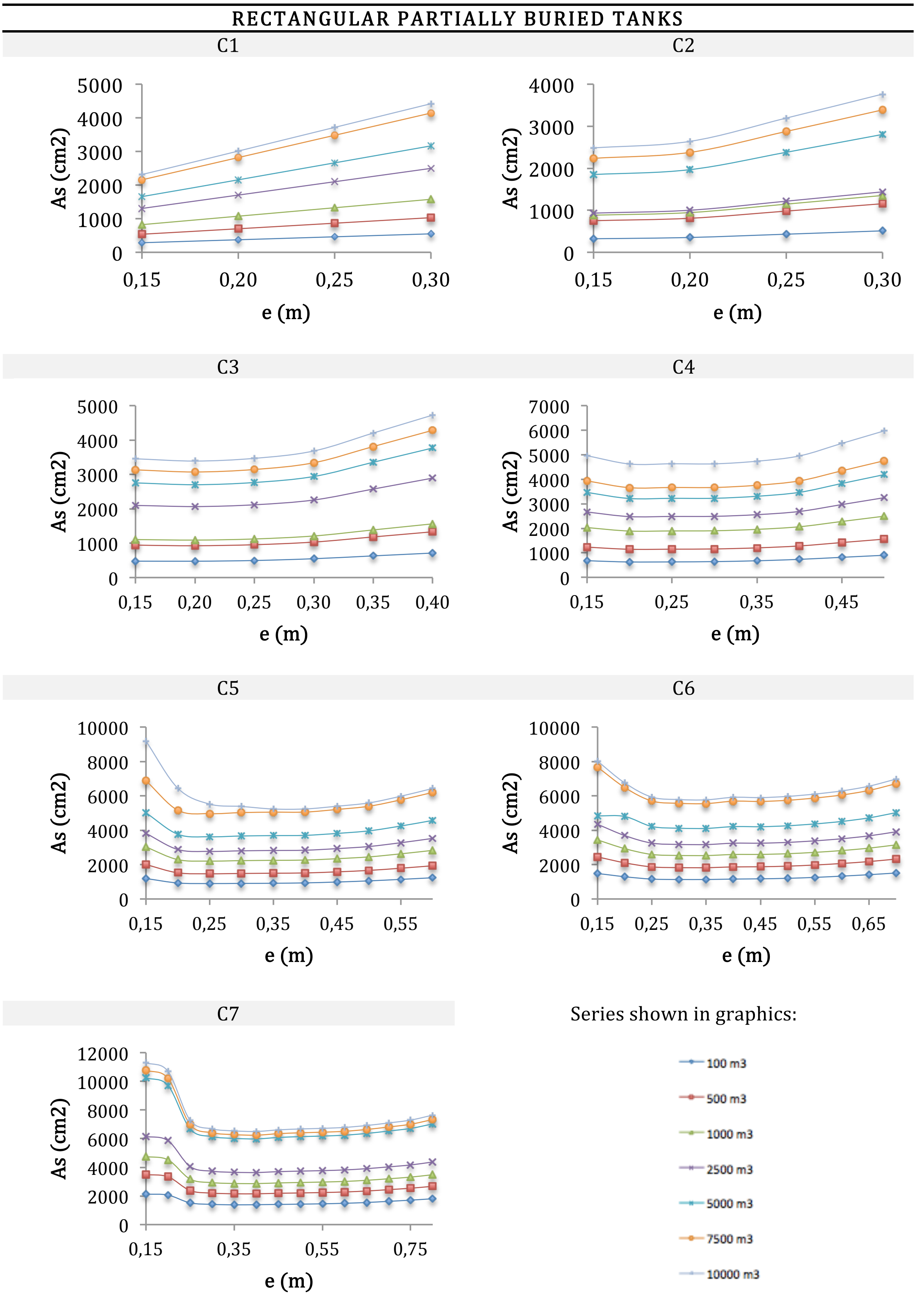


Figure B.45s f(e) Reinforcement ratio variation depending on the wall thicknesses evaluated for each volume in Rectangular partially buried tanks

APPENDIX B

PARAMETRIC STUDY FOR LCA

1. INTRODUCTION

The aim of this appendix is to present all the cases results that in order to do the environmental study are used. The results correspond to the case studies detailed in the Figure 5.1 of chapter 5 and are presented in terms of materials required amount to develop the structural design.

2. CONCRETE CONSUMPTION RESULTS

Table B.1 shows the amount of concrete required for the construction of the most optimal configuration established for the different volume cases studied.

Table B.1 Concrete amounts for each optimal configuration in every volume analyzed.

VOLUME (m3)	OPTIMAL CASE	V CONCRETE (m3)
(a= 8,00 m ; R= 2,00 m)	100	38
(a= 8,00 m ; R= 4,50 m)	500	106
(a= 8,00 m ; R= 6,50 m)	1.000	178
(a= 8,00 m ; R= 10,00 m)	2.500	339
(a= 8,00 m ; R= 14,50 m)	5.000	615
(a= 8,00 m ; R= 17,50 m)	7.500	841
(a= 8,00 m ; R= 20,00 m)	10.000	1056

3. STEEL CONSUMPTION RESULTS

Table B.2 shows the amount of steel required of the construction of the different configurations established for the different volume cases studied.

Table B.2 Concrete amounts for each optimal configuration in every volume analyzed.

e=0,3		PARTILLA BURIED TANKS		SURFACE TANKS		BURIED TANKS	
		cm²	kg	cm²	kg	cm²	kg
100 m³	C1 (a=2,00 ; R=4,00)	576,7	11896	576,7	11896	576,7	11896
	C2 (a=3,00 ; R=3,30)	490,7	8198	490,7	8198	490,7	8198
	C3 (a=4,00 ; R=3,00)	460,1	6806	460,1	6806	460,1	6806
	C4 (a=5,00 ; R=2,60)	415,7	5253	415,7	5253	415,7	5253
	C5 (a=6,00 ; R=2,40)	399	4626	399	4626	399	4626
	C6 (a=7,00 ; R=2,20)	390,9	4117	390,9	4117	390,9	4117
	C7 (a=8,00 ; R=2,00)	384	3725	384	3725	384	3725
500 m³	C_1 (a=2,00 ; R=9,00)	1270	59899	1270	59899	1270	59899
	C_2 (a=3,00 ; R=7,50)	1073,1	41657	1073,1	41657	1073,1	41657
	C_3 (a=4,00 ; R=6,50)	946,7	31491	946,7	31491	946,7	31491
	C_4 (a=5,00 ; R=5,70)	869,7	24384	869,7	24384	869,7	24384
	C_5 (a=6,00 ; R=5,20)	840,3	20660	840,3	20660	840,3	20660
	C_6 (a=7,00 ; R=4,80)	830	18101	830	18101	830	18101
	C_7 (a=8,00 ; R=4,50)	838,5	16424	838,5	16424	838,5	16424
1000 m³	C_1 (a=2,00 ; R=13,00)	1824,7	125037	1824,7	125037	1824,7	125037
	C_2 (a=3,00 ; R=10,50)	1489,1	81563	1489,1	81563	1489,1	81563
	C_3 (a=4,00 ; R=9,00)	1300,3	60045	1300,3	60045	1300,3	60045
	C_4 (a=5,00 ; R=8,00)	1206,9	47848	1206,9	47848	1206,9	47848
	C_5 (a=6,00 ; R=7,50)	1194,8	42365	1194,8	42365	1194,8	42365
	C_6 (a=7,00 ; R=7,00)	1189,9	37571	1189,9	37571	1189,9	37571
	C_7 (a=8,00 ; R=6,50)	1189,8	33293	1189,8	33293	1189,8	33293
2500 m³	C_1 (a=2,00 ; R=20,00)	2795,3	295966	2941,2	311389	2795,3	295966
	C_2 (a=3,00 ; R=16,50)	2321	201283	2321	201283	2321	201283
	C_3 (a=4,00 ; R=14,50)	2069,1	155694	2069,1	155694	2069,1	155694
	C_4 (a=5,00 ; R=13,00)	1926,6	125526	1926,6	125526	1926,6	125526
	C_5 (a=6,00 ; R=12,00)	1952,8	112683	1952,8	112683	1952,8	112683
	C_6 (a=7,00 ; R=11,00)	1963,3	99348	1963,3	99348	1965,2	99416
	C_7 (a=8,00 ; R=10,00)	1950,5	85434	1950,5	85434	1981,4	87061
5000 m³	C_1 (a=2,00 ; R=28,50)	4147,7	626475	5075,1	767539	3974	600303
	C_2 (a=3,00 ; R=23,50)	3291,7	408396	3715,2	461346	3291,7	408396
	C_3 (a=4,00 ; R=20,00)	2830,2	296127	2945,3	308297	2830,2	296127
	C_4 (a=5,00 ; R=18,00)	2803,5	256293	2803,5	256293	2803,5	256293
	C_5 (a=6,00 ; R=16,50)	2856,4	230969	2856,4	230969	2946,9	238922
	C_6 (a=7,00 ; R=15,50)	2976,1	217458	2976,1	217458	3170,4	233427
	C_7 (a=8,00 ; R=14,50)	3070,5	200938	3070,5	200938	3337,6	221554
7500 m³	C_1 (a=2,00 ; R=35,00)	5750	1068255	7617,8	1416384	4875,3	905050
	C_2 (a=3,00 ; R=28,50)	3985	600350	5054,9	762779	3985	600350
	C_3 (a=4,00 ; R=24,50)	3473	446680	3976,2	512364	3473	446680
	C_4 (a=5,00 ; R=22,00)	3552,2	400480	3800,5	429506	3619,1	408299
	C_5 (a=6,00 ; R=20,00)	3616,3	358965	3700,7	367881	3861,7	385112
	C_6 (a=7,00 ; R=18,50)	3717,6	328672	3717,6	328672	4094,2	365675
	C_7 (a=8,00 ; R=17,50)	3902,4	313606	3902,4	313606	4396,6	359679
10000m³	C_1 (a=2,00 ; R=40,00)	7693,7	1635106	10235,2	2181129	6266,3	1331227
	C_2 (a=3,00 ; R=33,00)	4649,1	820777	6734,2	1178438	4609	804872
	C_3 (a=4,00 ; R=28,50)	4093,1	614685	5131,8	772306	4093,1	614685
	C_4 (a=5,00 ; R=25,50)	4232,3	556282	4820,1	636168	4410,1	580401
	C_5 (a=6,00 ; R=23,50)	4422,3	520592	4782,2	565613	4870,9	576656
	C_6 (a=7,00 ; R=21,50)	4508,9	468804	4681,7	488493	5158,5	543024
	C_7 (a=8,00 ; R=20,00)	4645,7	432388	46998,	438050	5458,6	518900